

**Energy Research and Development Division  
FINAL PROJECT REPORT**

# **ADVANCED 6.7 LITER NATURAL GAS ENGINE DEVELOPMENT**

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Prepared by: Gas Technology Institute and Cummins Westport Inc.

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## PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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## ABSTRACT

Engines that use natural gas produce fewer greenhouse gas emissions than those that use petroleum fuels. However, the current North American commercial vehicle market lacks a natural gas-powered engine compatible with Class 3 through 7 consumer vehicles. To meet this need, the research team designed, developed, and demonstrated an Alpha stage 6.7 liter natural gas engine designated as the ISB6.7 G. This engine was developed using stoichiometric cooled exhaust gas recirculation spark ignition technology capable of meeting the United States Environmental Protection Agency and California Air Resources Board's 2013 emission standards for nitrous oxides, carbon monoxide, nonmethane hydrocarbons, and particulate matter, as well as the United States Environmental Protection Agency's 2017 greenhouse gas emission standards.

The research team followed the Cummins process for developing, validating, and commercializing new engines to design the ISB6.7 G engine. During the Alpha design stage, the engine components were optimized through modeling analysis, bench tests, and engine laboratory experience with the goal of assessing the design capability to meet targets. Tests verified that the pre-Alpha and Alpha versions of the ISB6.7 G met these key performance targets.

All original equipment manufacturer launch partners are committed to the ISB6.7 G and have either validated their installations using Alpha engines or will do so using Beta engines. The Beta phase and commercialization is not included in the scope of this project, but has already begun at the Cummins Rocky Mount Engine Plant Facility.

**Keywords:** California Energy Commission, Natural Gas, stoichiometric, spark ignited, SESI, exhaust gas recirculation, 6.7 Liters, ISB6.7 G, ISL G, ISX12 G, CWI, engine, emissions, catalyst, compression, design

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# EXECUTIVE SUMMARY

## Introduction

The market demand for natural gas-powered commercial vehicles has increased significantly in recent years. However, the lack of variety in the range of medium-and heavy-duty natural gas engines available to the North American commercial vehicle market compared to the range of available diesel engines is hindering continued expansion of natural gas market penetration. Currently, there is no natural gas engine available that is ideally suited for Class 3 through 7 commercial vehicle markets. These vehicle classes typically use six to eight liter diesel engines with specific power output and peak torque requirements. Due to the lack of appropriately sized natural gas engines in the North America market, the natural gas market share is negligible in the majority of these market segments. Some original equipment manufacturers (OEMs) and end-users have elected to use larger engines, such as Cummins Westport Inc.'s (CWI) 8.9 liter ISL G engine, to enable partial natural gas engine penetration in commercial vehicles such as yard tractors, rear-engine style transit-buses, and Type D school buses. However, these engines are larger and more expensive than the engine models typically used in the Class 3 through 7 target markets, and as a result, may not be cost-effective for many customers in the target markets. In the majority of cases, installing larger engines is not possible due to physical packaging constraints in the engine bays of the vehicles used in these applications.

To address the shortage of suitable natural gas engine technology available to the California and wider commercial vehicle markets and to optimize the performance and fuel economy of spark-ignited natural gas engines in Class 3 through 7 truck and bus applications, the research team developed a low-emission, high-performance, and high-efficiency 6.7 liter natural gas engine called the ISB6.7 G. The design of the ISB6.7 G is based on a Cummins ISB6.7 diesel engine platform integrated with CWI's stoichiometric cooled exhaust gas recirculation spark ignition (SESI) technology.

The research team's new engine will provide a common platform for diesel and natural gas engine products in the North American medium-duty truck market for many years to come. The market penetration of natural gas engines for commercial vehicle applications will be enhanced when common diesel and natural gas base engine platforms are made available. By leveraging diesel engine integration work, common base engine platforms enable vehicle OEMs to minimize the cost of installing natural gas engines into vehicles. Minimizing OEM installation costs in turn lowers vehicle cost and price, which leads to increased availability of natural gas engines to end users and greater natural gas penetration in medium-duty commercial vehicle markets.

## Project Purpose

The research team sought to design, develop, and demonstrate a pre-commercial spark ignited natural gas engine with ultra-low emissions, high performance, and best-in-class fuel economy for specific Class 3 through 7 truck and bus duty cycles. The emission, performance, and fuel economy benefits can be achieved by applying CWI's SESI technology to the Cummins ISB6.7

diesel engine platform. In accordance with the Cummins-prescribed process for early stage technology development, performance was to be demonstrated through engine dynamometer testing and vehicle performance simulation modeling.

The objectives were to:

- Design, develop, and demonstrate (on an engine dynamometer) an Alpha stage 6.7 liter medium-duty natural gas engine that can be certified at or below United States Environmental Protection Agency (U.S. EPA) and California Air Resources Board (ARB) 2013 emission standards
- Demonstrate a peak rating of 260 hp and a peak torque of 660 lbs-ft
- Improve fuel economy by 5 percent to 10 percent compared to CWI's 5.9 liter lean burn spark ignition natural gas engine that CWI sold in the North American market through 2009
- Demonstrate levels of greenhouse gas (GHG) emissions (carbon dioxide [CO<sub>2</sub>], methane [CH<sub>4</sub>], and nitrous oxide [N<sub>2</sub>O]) that will enable emission certification at or below the U.S. EPA 2017 GHG emissions standards

## Project Results

The research team achieved all the objectives of the project. CWI decided to base the development of the new ISB6.7 G natural gas engine on the design of their ISB6.7 diesel engine.

During the pre-Alpha phase of the development process, the researchers defined and verified the engine architecture through analytical models, calculations, and testing to achieve initial verification of performance targets. The knowledge gained from the pre-Alpha engine operation helped the research team optimize and create a production intent Alpha engine and engine component designs.

The researchers upfitted approximately 5 field test vehicles with Alpha engines to operate in real world applications, such as school bus, transit/shuttle, delivery truck, yard spotter, and sweeper applications. Additional vehicles will be upfitted with Beta engines following expected beta engine production in 2016. Preliminary emission, fuel consumption, and GHG data from the engine test cells indicate that the engine design achieves the design targets for the program. Additional development work will continue throughout the program to further validate the engine design in preparation for emission certification and commercial product launch.

This project ended with the Alpha engine design, build, and validation testing phase. Final development, which will include the Beta phase and will lead to commercialization, was not included in the scope of this project; however, CWI has already begun this development phase. The research team followed the Cummins process for developing, validating, and commercializing new engines. This process brought together a cross-functional Core Team with defined tasks during each phase of development. From the start of the development process to the commercialization of the product, CWI has engaged external stakeholders including Cummins Distribution and Service networks, government agencies (such as U.S. EPA and

ARB), and fleets to transfer the experimental results and other knowledge gained during the process. All truck OEM launch partners are committed to final development and have either validated their installations using Alpha engines or will do so using Beta engines. All OEMs will be required to comply with Cummins installation quality assurance requirements prior to approval for receiving production engine shipments to insure quality.

The Cummins Rocky Mount Engine Plant facility is scheduled to commence building the Beta engine, which will be comprised of over 80 percent production parts, into the first half of 2016. New tooling for the ISB6.7 G cylinder head has been validated on the Alpha build engines and will be further validated on the upcoming Beta engine build prior to full production.

CWI recommends proceeding with the next stage of the overall ISB6.7 G engine development, demonstration, and commercialization. CWI has initiated the next phase of the development work with an objective of continuing Beta engine build into early 2016 and adding Beta engines to the existing Alpha customer field demonstrations. This leads to commercial availability of the ISB6.7 G engine in a broad range of Class 5 to 7 vehicles, including medium-duty trucks, school buses, shuttle buses, yard tractors, and municipal works vehicles such as street sweepers in 2016. CWI anticipates that the total expense to enable ISB6.7 G commercial availability will be in the range of \$2 million to \$4 million.

### Project Benefits

The 6.7 liter natural gas engine can consume either compressed natural gas (CNG) or liquefied natural gas (LNG), although most applications are expected to use CNG stored fuel. Natural gas can produce fewer GHG emissions than petroleum fuels. ARB's Low Carbon Fuel Standard helped forecast the GHG reductions associated with vehicles powered by the ISB6.7 G natural gas engine by calculating the full fuel cycle GHG emissions on a per vehicle per year basis. For the purpose of calculating total GHG emissions, a *base case* was identified for natural gas fuel supply, assuming that 90 percent of the natural gas fuel consumed by the ISB6.7 G-powered fleet will be derived from conventional natural gas fuel pathways and 10 percent from biomethane pathways. An *upside case*, which assumes that 50 percent of the fuel consumed by the fleet will be derived from biomethane pathways, was also calculated. The predicted GHG emission reductions of the ISB6.7 G (relative to a diesel vehicle) are 31.9 percent for the base case (10 percent renewable fuel) and 56.2 percent for the upside case (50 percent renewable fuel).

The ISB6.7 G engine is expected to increase natural gas products available to the California commercial vehicle market by introducing a spark-ignited, natural gas engine product optimized for both performance and fuel economy in Class 3 through 7 truck and bus applications. By developing and subsequently commercializing a low-emission, high-performance, and high-efficiency 6.7 liter natural gas engine for these applications, a viable alternative to diesel engines currently serving this market will become available. The natural gas engines currently available to serve these applications, consisting mostly of after-market conversions, are not considered optimized for fuel efficient performance. Accordingly, the natural gas ratepayers who purchase the proposed new ISB6.7 G natural gas engines in the future are expected to directly benefit from cost savings per mile traveled. This high-efficiency

engine will also reduce the emissions of criteria pollutants and GHG emissions per mile traveled.

Natural gas ratepayers will also benefit from consuming less diesel fuel as the ISB6.7 G engine displaces diesel in the target market application. Natural gas use will lessen petroleum imports used for the affected duty cycle market. This reduced demand for diesel should enable greater gasoline production from capacity constrained refineries, which should help mitigate volatility in gasoline prices.

Commercial availability of the ISB6.7 G engine will help enable natural gas adoption in the Class 5 through Class 7 truck market as well as the school bus and shuttle bus markets. This increased availability will significantly increase both the demand for new natural gas fueling stations and the use of existing ones along with promotion and incentives for biomethane (or *renewable natural gas*) production. The demand for more natural gas fueling stations will create jobs in California, which in turn will create permanent jobs related to the collection, treatment, dispensing, and distribution of bio methane for transportation purposes from renewable resources including landfills, dairies, and sewage treatment facilities.

# CHAPTER 1:

## Task 2 – Pre-Alpha Engine Design, Build, and Test

### 1.1 Pre-Alpha Design and Build

The pre-Alpha phase of the development process is used to define and verify engine architecture. In addition to analytical models and calculations, it is common (but not mandatory) at this phase to provide evidence by testing that all performance targets are achievable.

The first step in architecture verification is achieved through the application of analysis tools. Analysis tools used prior to engine build and test include:

- Design Failure Mode Effects Analysis (DFMEA)
- Computer Assisted Design (CAD) layout (Pro Engineer by Parametric Technologies)
- Engine performance model (GT-Power by Gamma Technologies)
- Combustion modeling (KIVA by Los Alamos National Lab)
- Finite Element Analysis (FEA)
- Computational Fluid Dynamics (CFD)

In parallel to the above analysis activity, a *mule engine* was built to assist in the correlation of analysis data with empirical test data. The mule engine is an engine prepared for use in a test cell only, with limited expectations for durability. Hardware for the mule engine was prepared and built as follows:

- An ISB6.7 diesel engine was obtained as a starting point.
- Cylinder heads were machined from diesel castings and components. The spark plug bore was specially machined, but all other features are diesel-like. The diesel valve train is used.
- The valve cover is an ISB6.7 diesel cover with special features added (welded & machined) in place to accommodate spark plug coils.
- The wire harness used is a modified ISLG harness.
- The electronic control module (ECM) and ignition control module (ICM) are mounted onto a fabricated steel plate.
- The turbocharger used is of the correct family (appropriate wheel sizes defined by GT Power model) but without any other enhancements. The turbo mounted to Pre-Alpha hardware utilizes prototype designs that accurately simulate engine performance, but may not represent production-intent geometry. In addition, pre-Alpha hardware may be

manufactured using non-production processes. The turbo mounts to an ISB6.7 diesel exhaust manifold using an adapter plate.

- Several variants of pistons were made from diesel aluminum flat tops wherein the piston bowl is machined using the output of KIVA modeling. Five different piston bowls were manufactured for use in narrowing the scope of the pre-Alpha bowl.
- The fuel module is a modified ISLG fuel module mounted using a special adapter plate.

Using the mule engine, the team was able to provide useful data to assist in the design of the pre-Alpha engines. Piston design was reduced from five versions on the mule to two for pre-Alpha testing. The diesel exhaust gas recirculation (EGR) system was verified. Peak torque and power were also verified. Heat rejection was measured, noted, and used for chassis planning. Various temperatures were recorded and used for the pre-Alpha design.

The pre-Alpha engines differed from the mule engine in that pre-Alpha engines were intended to:

- Be more robust.
- Be capable of being used in the test cell and in vehicles.

The following are key differences (improvements) made from the mule version of the engine to the pre-alpha version:

- Steel pistons
- Newly designed fuel module
- Closed crankcase ventilation
- Newly designed 3-piece exhaust manifold (Turbocharger mounts directly to the manifold)
- Cylinder head with production-intent (natural gas) components

With the design information mentioned above, all seven pre-Alpha engines were built at our production location on the high volume assembly line:

- To give manufacturing personnel experience with the new hardware and allow feedback so the design team can apply 'design for assembly' changes in the Alpha stage.
- To provide an engine with consistent assembly process to create more uniformity.
- To prevent mistakes generated with an off-line process.

During the pre-Alpha process, engines were tested in three locations:

- Cummins Technical Center, performance cell, Columbus, Indiana
- Intertek Testing, endurance cell, San Antonio, Texas

- Freightliner truck, model M2, Columbus, Indiana

Engine testing in the performance cell verified many of the critical performance and mechanical targets (shown in Table 1) for the following test and design attributes:

- Primary heat rejection and exhaust temperature data
- Piston selection
- Piston pin joint abuse test
- Preliminary oil consumption data
- Verify turbocharger wheel match
- Verify turbine inlet temperatures
- Verify fuel module function
- EGR system verification
- Combustion face temperature measurements
- Develop/tune spark timing, knock, and misfire algorithms

## **1.2 Pre-Alpha Testing**

The pre-Alpha phase of the project consists of both performance and mechanical development testing. This section summarizes the testing.

### **1.2.1 Performance Testing**

A key activity for pre-Alpha is to verify that the engine architecture selected will deliver the required performance. A pre-Alpha engine was installed into a dedicated natural gas test cell at Cummins Technical Center, Columbus, Indiana. Figure 1 and Figure 2 are photos of the installation.



**Figure 1: Pre-Alpha Engine Installed Cummins Tech Center**

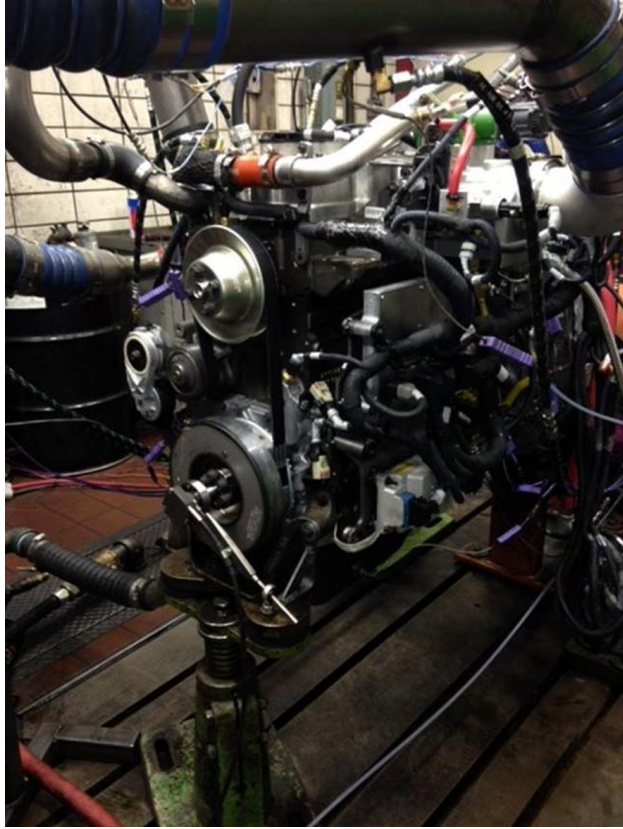


Photo Credit: Cummins Westport Inc.

**Figure 2: Pre-Alpha Engine Installed at Cummins Tech Center**

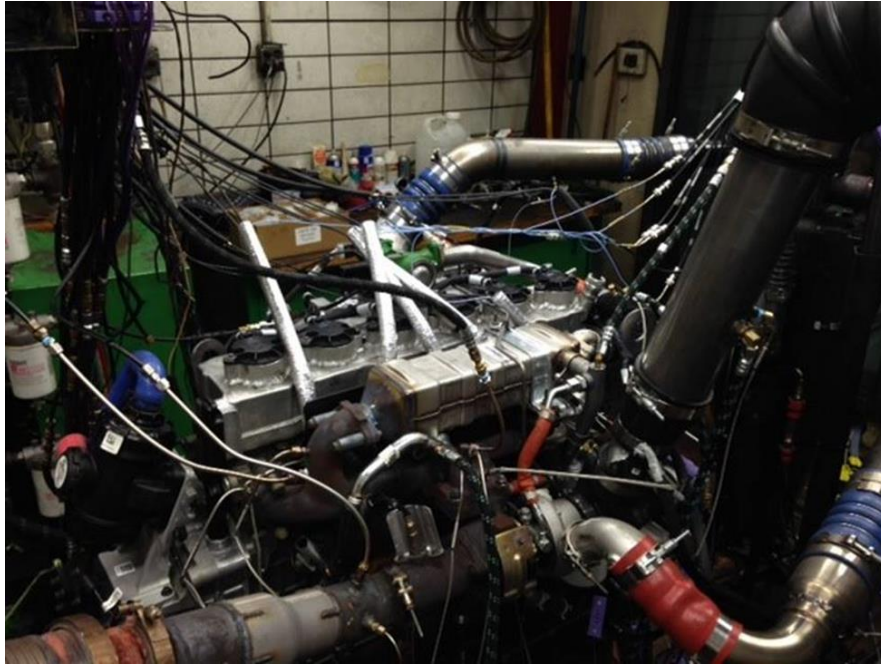


Photo Credit: Cummins Westport Inc.

#### *1.2.1.1 Verification of Critical Engine Performance Targets*

The engine has specific critical performance deliverables that were verified early in the pre-Alpha process. These targets are defined by gathering critical inputs from our key customers, also known as *the voice of the customer*. Table 1 shows our targets and a result of our testing.

**Table 1: Key Performance Targets and Status**

<b>Voice of the Customer DELIVERABLE</b>	<b>REQUIREMENT / DELIVERABLE</b>	<b>R/Y/G</b>	<b>PRE-ALPHA TEST RESULT: (Verification Method)</b>
Emissions - North America	U.S. EPA / ARB / EMD+		Status: Green Emissions for North America achieved using same catalyst as is used on ISLG engine. This will be the prime path for the ISB6.7G.
GREENHOUSE GAS - CH <sub>4</sub> EMISSIONS	Meet 2nd phase (2016) U.S. EPA MHD GHG regulations at launch		Status: Green To meet GHG target, CCV is required. CCV will be considered prime path moving forward.  NOTE: This will be re-examined at Alpha stage to determine if further

Voice of the Customer DELIVERABLE	REQUIREMENT / DELIVERABLE	R/Y/G	PRE-ALPHA TEST RESULT: (Verification Method)
			'tuning' will allow us to meet the GHG target without CCV.
Noise	< 80 dBA drive-by		Status: Green Drive-by testing conducted at Cummins Noise Facility in Walesboro, Indiana. The testing, which used two different truck installations, demonstrated a pass per U.S. EPA test standards. The significance of the test is that, going forward, no additional noise abatement treatment or strategy will be pursued.
Peak Power	260 hp @ 2400		Status: Green Engine power achieved using worse case conditions (max water and air temperatures).
Peak Torque - North America	660 lb-ft @1600 rpm		Status: Green Engine torque achieved using worst case conditions (max water and air temperatures). NOTE: Turbocharger margin at peak torque is narrow, but acceptable. More attention to air handling altitude effects will be key focus at Alpha stage.
Responsiveness	1 & 2 second torque capability per VPP		Status: Green Throttle response demonstrated.
Heat Rejection	Combined heat rejection (coolant + CAC) no more than 35% greater than same ISB6.7 diesel ratings		Status: Yellow Heat rejection to coolant was higher than anticipated (~40% higher than diesel equivalent). This information is being shared with major OEM

Voice of the Customer DELIVERABLE	REQUIREMENT / DELIVERABLE	R/Y/G	PRE-ALPHA TEST RESULT: (Verification Method)
			customers to ensure that proper cooling system design is carried out with anticipation of higher than expected heat rejection.
Fuel Economy	15% less than ISB		Status: Yellow Although fuel consumption is noted and recorded at pre-Alpha stage, rigorous fuel economy measures and tuning were postponed until the Alpha phase. Fuel consumption is recognized as a critical deliverable and will be a key focus in Alpha.
Transmissions Compatibility	North America: Allison Auto 2000 & 3000 Series.		Status: Green Transmission tuning was conducted in chassis during pre-Alpha phase. No major issues encountered. NOTE: It was determined that the Allison 2500 series transmission will have some torque limitations that will require specific tuning in Alpha.

Photo Credit: Cummins Westport Inc.

**Figure 3: Demonstrated Engine Torque Curves**

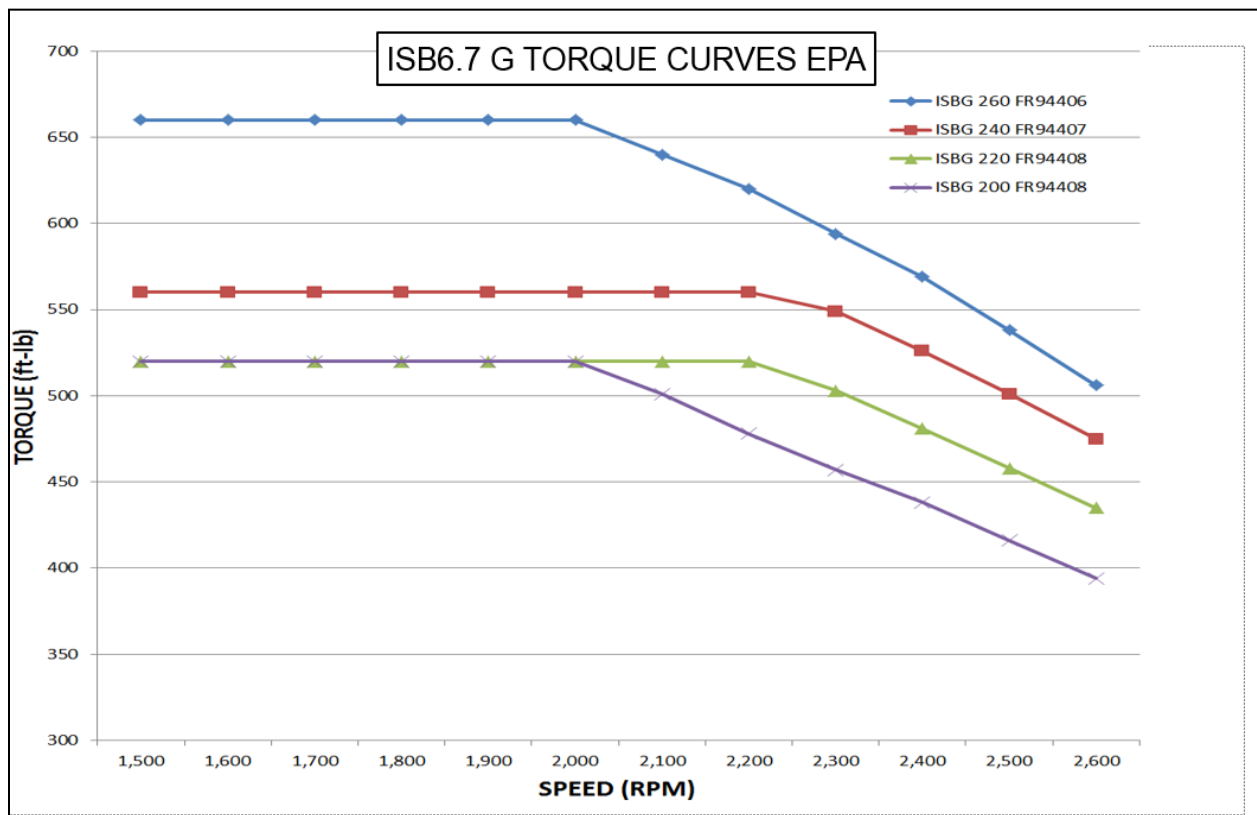


Photo Credit: Cummins Westport Inc.

#### 1.2.1.2 Engine Performance Tuning

The pre-Alpha engine was used to conduct critical tuning exercises in preparation for the Alpha stage of the program. The key focus of the performance tuning was to optimize the engine's ability to manage knock and misfire. This is achieved by balancing spark timing and EGR flow and temperature.

#### 1.2.1.3 Emissions Testing

**U.S. EPA emission limits were comfortably achieved during the testing and no further work was conducted. Significant focus will be dedicated to further emission work at the Alpha phase. See Table 2 and**

Table 3 for pre-Alpha emission testing results.

**Table 2: Emission Limits**

	<b>NO<sub>x</sub> (g/hp-hr)</b>	<b>CO (g/hp-hr)</b>	<b>NMHC (g/hp-hr)</b>	<b>PM (g/hp-hr)</b>	<b>GHG (g/hp-hr)</b>
<b>Limit</b>	0.2	15.5	0.14	0.01	576
<b>Deterioration Factor (DF)</b>	1.358	2.05	1	1	1
<b>Limit with DF</b>	<b>0.147</b>	<b>7.56</b>	<b>0.14</b>	<b>0.01</b>	<b>576</b>

Photo Credit: Cummins Westport Inc.

**Table 3: Pre-Alpha Emission Results**

	<b>NO<sub>x</sub> (g/hp-hr)</b>	<b>CO (g/hp-hr)</b>	<b>NMHC (g/hp-hr)</b>	<b>PM (g/hp-hr)</b>	<b>GHG (g/hp-hr)</b>
Cold Hot Emissions Test Federal Test Procedure	0.106	2.29	0.003	0.0004	505
RMCSET	0.012	1.02	0.0002	0.0003	468.6
Limit	0.2	15.5	0.14	0.01	576
Limit with DF	0.147	7.56	0.14	0.01	576

Photo Credit: Cummins Westport Inc.

### 1.2.2 Mechanical Development Testing

In addition to engine performance, there were a number of significant mechanical development exercises conducted on the pre-Alpha hardware. All of these activities were conducted to provide confidence that our Alpha design intent is correct. Below is a list of those activities:

- Spark plug temperature measurements
- Valve cover vibration measurements
- Fuel system vibration
- Cylinder head temperature measurements (combustion face)
- Coolant flow
- Piston pin seizure test
- Idle oil consumption
- Urban bus duty cycle analysis (for turbocharger compressor wheel reliability analysis)
- Thermal cycle test (early cylinder head reliability – 750 hours)

## CHAPTER 2:

### Task 3 – Alpha Engine Design and Build

The goal was to apply knowledge gained from the concept engine operation and begin optimizing the engine and engine component designs based on modeling analysis, bench tests, and engine laboratory experience. This leads to the building of representative engines to further assess the design capability to meet targets.

While early engine concept design used existing components wherever possible, the Alpha design strives for *production intent* design components. Accordingly, it represents the first design phase that focuses on creating component and sub-system designs for high-volume manufacturing. This chapter describes the Alpha design for the various major sub-systems that comprise the ISB6.7 G engine, as well as photos and CAD models of the overall Alpha engine design.

#### 2.1 Base Engine

The Cummins ISB6.7 Diesel Engine is the Base Engine Platform for CWI's Engine Development Program. Cummins initiated commercial availability of the ISB6.7 diesel engine in January 2013. See Figure 4 for a photo of the diesel engine.

**Figure 4: ISB6.7 G Alpha Engine**



Photo Credit: Cummins Westport Inc.

CWI will retain the majority of the base engine for the ISB6.7 G Alpha design, including the cylinder block, crankshaft, connecting rods, main bearings, engine mounts, external accessories (for example, air compressors, alternators, starting motors, fan hubs, and so forth), and customer selectable options—such as flywheel housing, oil pan, and oil level gauge.

CWI's development of the ISB6.7 G engine focuses on unique designs for major engine subsystems, which are summarized below.

## 2.2 Power Cylinder

The ISB6.7 G engine requires a unique piston design capable of providing the required compression ratio, optimized for in-cylinder conditions with spark ignition combustion, and offering durability required when applying the SESI technology. CWI identified a number of candidate piston designs based on analytical modeling and assessed those designs based on concept engine testing. During the Alpha design process, the piston design was refined based on test data and further analytical modeling. The piston design selected is based on the best combustion rate predicted from combustion models, while ensuring that the design yields acceptable maximum cylinder head temperatures. Throughout the design process, finite element analysis and in-cylinder temperature measurements were used to quantify the piston's peak operating temperatures. The resulting Alpha piston design and associated peak temperature distribution are shown in Figure 5.

**Figure 5: Piston Temperature Distribution**

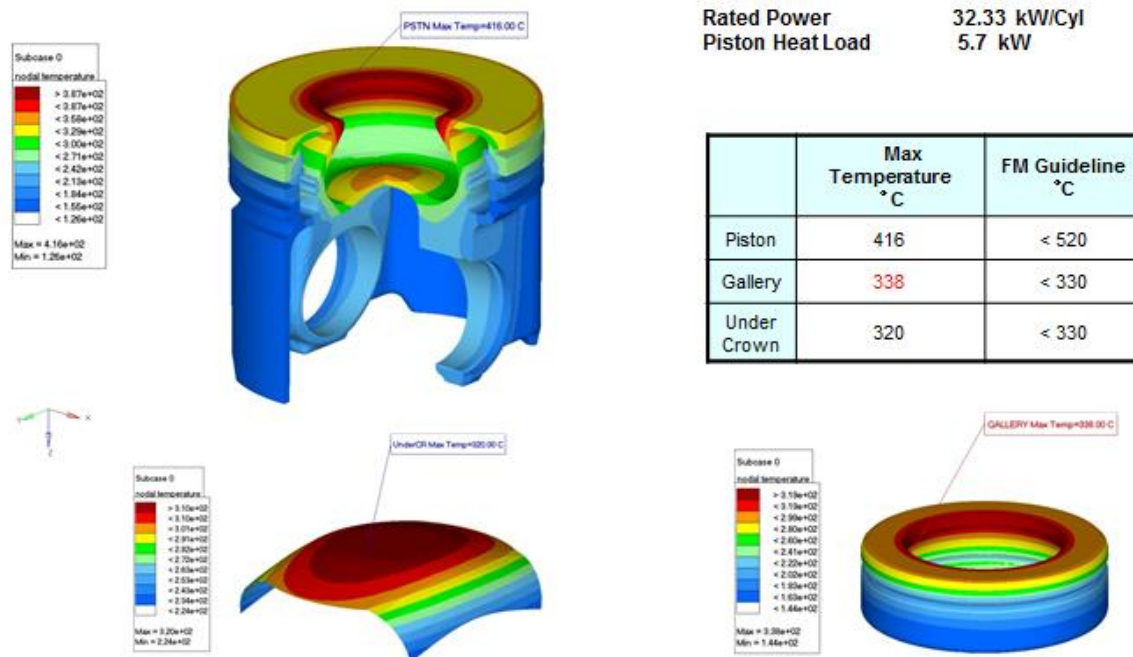


Photo Credit: Cummins Westport Inc.



## 2.3 Electronic Control System

The electronic control system design is direct *carry-over architecture* from the ISL G and ISX12 G engines. The control system design consists of ECM, sensors, actuators, wire harnesses, and software and calibrations.

During the Control System Alpha design phase, CWI concluded that no ECM hardware modifications were required. However, unique software and calibrations were required to enable certain electronic features that had not previously been developed for CWI's natural gas engines and were unique to the ISB 6.7 diesel engine. The following is a list of unique features for the ISB6.7 G engine:

- Switchable Governor Type: feature allows the OEM to select either a torque-controlled or speed-controlled governor for the accelerator input.
- Idle Shutdown - Ambient Temperature Override: feature overrides an engine shutdown initiated by the Idle Shutdown feature when the ambient air temperature is below a threshold.
- Power Take Off Stationary Pumping: feature used when an automotive engine is used for pumping operations while the vehicle is stationary.
- Road Speed Governor - Switched Maximum Vehicle Speed: feature allows the customer to use a switch to set a vehicle speed limit for two different maximum vehicle speeds.
- Auxiliary shutdown: set up as an additional switched input for engine shutdown to the regular Engine Protection feature.

Additional software and calibrations will be required to comply with the applicable on-board diagnostics (OBD) requirements; however, OBD-specific development is not included within the scope of the Alpha development. OBD development and validation will be conducted during the next phase of the ISB6.7G engine development program.

## 2.4 Ignition System

The ignition system consists of the following components:

- ICM
- Ignition harness
- Ignition coils
- Ignition coil extensions (to connect the ignition coil to the spark plug)
- Spark plugs
- Calibration

The ignition system architecture consists of coil-on-plug technology and an ICM that are consistent with CWI's ISX G engine. While the ignition system architecture is identical to CWI's existing ISX12 G engine, the design packaging of the ISB6.7 G engine presents unique challenges. For example, design layout and packaging studies for the 6.7 have driven packaging of the ICM in a different orientation and location on the engine than on the ISX12 G. On the ISB6.7 G, the ICM will be located on top of the engine, directly behind the fuel module assembly. This change is expected to improve and shorten the routing of the ICM harness as well as improve serviceability. The ISB6.7 G ignition coils are mounted to the valve cover, which is directly above the spark plugs that are mounted in the cylinder head, with ignition coil extensions connecting the coils to the plugs. To accommodate the packaging limitations imposed by the air cleaner assembly, the ignition coil design provides minimal clearance above the valve cover while enabling ignition harness connections. Figure 6 and Figure 7 identify the ignition system components and their mounting configuration. (Note that this arrangement is nearly identical of that used on the ISX12 G engine with several parts being common.)

The ignition harness has a new feature included in the design. The harness was enhanced with the addition of several grounding points to reduce radiated electronic noise emissions. The goal of the program is to meet CISPR 25, class 1 radiated emission levels (30 Volts per meter).

**Figure 6: Ignition System Hardware**

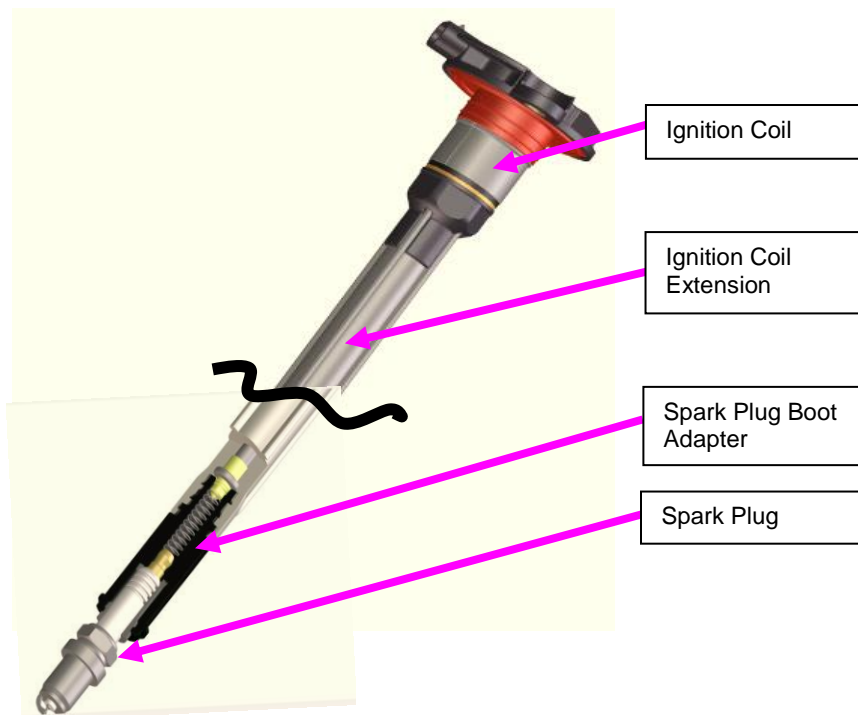


Photo Credit: Cummins Westport Inc.

**Figure 7: Ignition Coils and Extensions Mounted to Valve Cover**

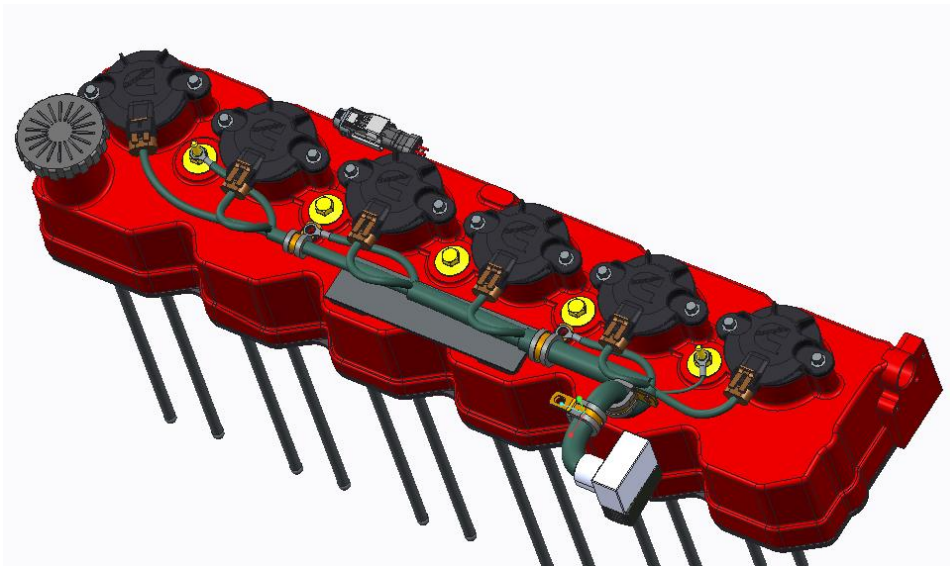


Photo Credit: Cummins Westport Inc.

## **2.5 Cylinder Head and Valve Train**

The ISB6.7 G cylinder head is modified from the base diesel head to improve thermal fatigue life and to accommodate spark plugs rather than diesel fuel injectors. Spark plug bore machining takes the place of the injector bore. In addition, shallow ‘scalloped’ cuts are added to the combustion face of each cylinder to improve thermal fatigue characteristics of the design. Lastly, the cast properties have changed from the diesel norm of gray iron to an alloyed iron with molybdenum added to improve thermal fatigue strength.

The ISB6.7 G valve train includes a number of changes to improve reliability. High temperature valve and seat insert materials improve reliability. In addition, valve rotators improve valve life.

## **2.6 Air Handling System**

Due to the lower air flow requirements associated with stoichiometric combustion, the ISB6.7 G requires a smaller turbocharger than the base diesel engine. Therefore, the ISB6.7 G Alpha engine design required development of a unique turbocharger.

Based on analytical modeling and concept engine test results, an optimal turbine casing size was selected. Using experience from previous gas engine projects, the ISB product will have a turbine housing that has higher temperature capability than any of its gas engine predecessors. The material to be used for the turbine housing is compacted graphite iron.

The change to compacted graphite iron will require a significant analysis and validation effort to confirm the integrity of the change. In addition to the material change, other changes are incorporated into the turbocharger assembly to improve overall robustness (see Figure 8).

**Figure 8: ISB6.7 G Turbocharger, Partial and Full Assembly Views**

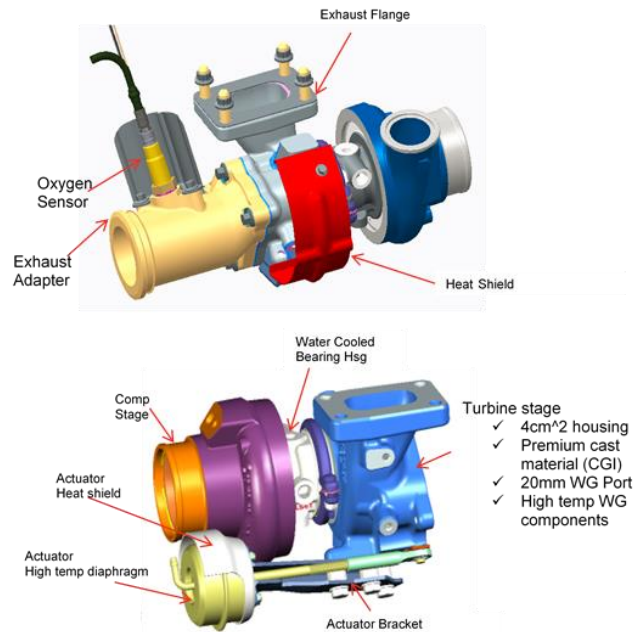


Photo Credit: Cummins Westport Inc.

## 2.7 Fuel System

The ISB6.7 G fuel system is architecturally similar to the ISL G engine and incorporates natural gas fuel supply, pressure regulation, metering and control, charge air throttling and measurement, and EGR control and mixing functions. Many of these functions are either not required on the diesel base engine or are handled elsewhere on the diesel engine. As a result of combining all these critical functions in one module for the natural gas engine, the fuel supply module is inherently larger than the diesel fuel components that it replaces on the intake side of the engine. As a result of the larger space claim required for the natural gas fuel supply module, CWI performed numerous design iterations in conjunction with various truck and bus OEMs. Figure shows an additional view of the module as mounted on the engine.

**Figure 9: Alpha Fuel Module Mounted on Engine**

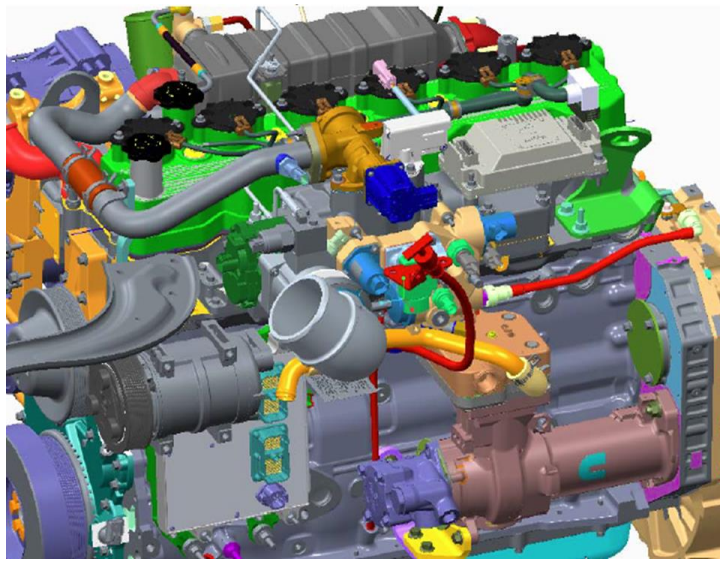


Photo Credit: Cummins Westport Inc.

## **2.8 Three-Way Catalyst**

The ISB6.7 G engine uses a three-way catalyst (TWC) to treat NO<sub>x</sub>, CO, and hydrocarbon (HC) emissions. CWI's 8.9 liter ISL G engine also uses a TWC for exhaust treatment. Early in the Alpha design, CWI investigated the feasibility of using the existing ISL G TWC with the 6.7 liter engine. Analysis and measurements performed on pre-Alpha engines confirm that the ISL G TWC is an acceptable emission solution for the 6.7.

## **2.9 Closed Crankcase Ventilation System**

At Alpha design stage, the ISB6.7 G engine evaluated the use of a crankcase gas recirculation system to capture blow by gases that are often exhausted to atmosphere with a diesel engine. On natural gas engines, the crankcase emission gases contain a significant amount of unburned methane gas. The objective of the recirculation system is to recirculate the unburned methane back through the engine rather than allowing it to escape to the atmosphere.

Although the engine is likely able to meet the 2016 North America Greenhouse Gas limits without a crankcase gas recirculation system, using the Closed Crankcase Ventilation system could provide additional margin for emission control and in turn allow the performance engineering team to better tune overall engine combustion. The ISB6.7 G system routes the gases from the valve cover through a filter and back to the compressor inlet of the turbocharger. Specially designed valves are used to make sure the pressure is carefully controlled. To avoid high oil consumption and 'fouling' of the compressor wheel, a crankcase gas filter will separate a high percentage of the oil carried along by the crankcase gases. That oil is agglomerated and returned to the oil pan through a drain tube and check valve system.

# CHAPTER 3:

## Task 4 – Alpha Validation Testing and Preliminary Beta Design

### 3.1 Subsystem Validation of Commercial Vehicle Requirements

The critical product requirements for the ISB6.7G product are gathered from Voice of the Customer interviews, ESW standards, and past experience with other Cummins Westport and Cummins Diesel products. From those inputs, a design validation plan and reporting is established and executed to validate the product.

Table 4 below lists the critical deliverables for the ISB6.7G from the voice of customer inputs, and the results of the validation / verification exercises.

**Table 4: Critical Deliverables from ISB6.7 G ‘Voice of Customer’**

<b>Deliverable</b>	<b>Requirement / Deliverable</b>	<b>Demo'd Date</b>	<b>Validation Status 12/9/14 (Verification Method)</b>
Emissions – North America	U.S. EPA / ARB / EMD+	03/30/14	Emission capability demonstrated on pre-Alpha engines with representative hardware. Same catalyst architecture as CWI's ISL G engine (see Table 3).
Greenhouse Gas – CH <sub>4</sub> Emissions	Meet 2 <sup>nd</sup> phase (2016) U.S. EPA MHD GHG regulations at launch	03/30/14	Engine very close to meeting GHG limits without CCV. Addition of CCV provides significant margin to be well under the requirements (see Table 3).
Noise	< 80 dBA drive-by	08/01/14	Both engineering trucks (FL M2 and Ford F750) pass the drive-by testing with only minor governor tuning required.
Reliability	RPH – 206 RPH @ launch	M3	Target reliability is difficult to demonstrate prior to completion of field tests. However, many 'fixes' from the existing CWI products have been integrated into ISB6.7 G and confidence is high based on results of the CWI warrant trend.
Peak Power	260 hp @ 2400 rpm	11/13/13	Demonstrated on pre-Alpha.
Peak Torque – North America	660 lb-ft @ 1600 rpm	11/13/13	Demonstrated on pre-Alpha.
Peak Torque – Europe	900 Nm @ 1300 rpm	11/13/13	Demonstrated on pre-Alpha.

Deliverable	Requirement / Deliverable	Demo'd Date	Validation Status 12/9/14 (Verification Method)
Responsiveness	1 & 2 second torque capability: % Full Load Torque <u>1s 2s</u> 800 rpm 60% 90% 1000 rpm 60% 90% 1200 rpm 60% 90% 1400 rpm 60% 90% 1600 rpm 60% 90% 1800 rpm 60% 90%	04/30/14	Demonstrated on pre-Alpha.
Fuel Economy	15% less than ISB diesel product	7/15/14	Have run VMS simulations comparing ISB6.7 G to ISB diesel. Fuel economy per the analysis is much better than 15% less than diesel.
Transmissions	Allison 2500 & 3000 series automatic's	9/1/14	Engineering and field test units have a mix of both these transmissions. Although not yet <i>flawless</i> , the units are functional and transmission tuning is <i>very near production-ready</i> .

Photo Credit: Cummins Westport Inc.

### 3.1.1 Dyno Validation

A key approach to validating the ISB6.7G is to run System Level Tests (SLTs) as developed by the Cummins Product Assessment Group. The SLT's are a series of tests designed to simulate "life" cycle of the engine in multiple applications. The following SLT's were applied and run on the ISB6.7G in 2014: SLT 2 – Thermal Cycle Test, SLT3 – Urban Bus Duty Cycle, Hot Box, Over Torque, Cycle Six, and Short Hour and Mapping.

SLT 2 – Thermal Cycle Test. This test simulates full-life deep thermal cycling of the engine. It is designed to ensure that the power cylinder, cylinder head, and exhaust system have sufficient thermal cycle robustness for the life of the product. In SLT 2, the engine is cycled with hot and cold air, as well as water during the test to simulate very extreme conditions. In addition, water is sprayed on the engine externally to provide additional shock and to validate electrical connections. Given the extreme conditions, this test is considered the most abusive and difficult SLT of the series. This test is run twice for the Alpha level product and once for the Beta level product. Test duration is 5000 thermal cycles (approximately 750 hours).

The variation of the exhaust temperature over one cycle of the test is shown in Figure 10.



**Figure 10: Exhaust Port Temperatures on SLT2 Cycle**

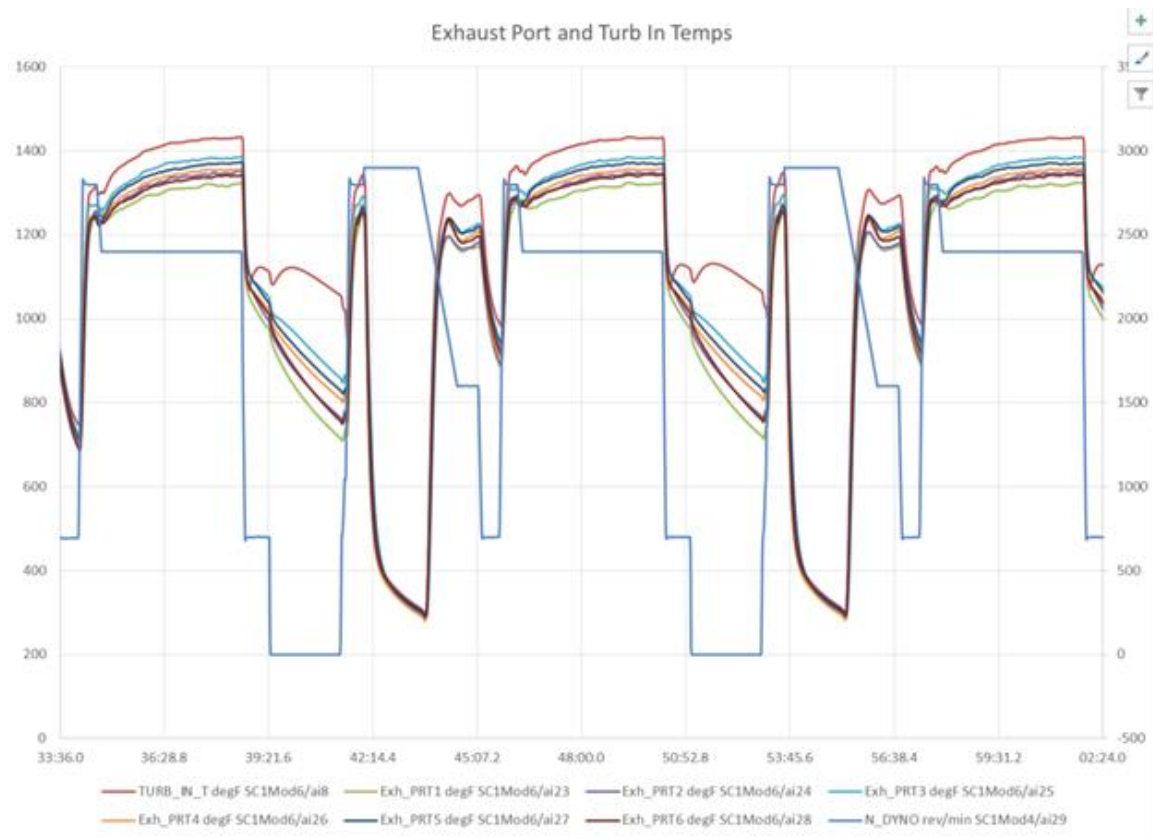


Photo Credit: Cummins Westport Inc.

Result of SLT2. The overall result is a pass. Engine condition at the end of the test was generally noted as “like new, gently worn.” The post test engine condition was recorded in Figure 11, Figure 12, Figure 13, Figure 14, Figure 15 and Figure 16. Several issues were captured and will be tracked using the Cummins Failure Incident Review Group (FIRG) process, which is a fundamental reliability process to ensure that all issues are resolved prior to product launch. One notable issue from the test was a cracked turbine housing, seen in Figure 14, which is being addressed with our internal supplier: Cummins Turbo Technologies. The issue will be tracked using formal Cummins issue-solving processes. This issue must be addressed prior to the Beta phase of the project. The issue resolution will likely require a small degree of change to the turbine housing casting to improve robustness of the design.



**Figure 11: Photo of SLT2 Engine *Post Test* (Note the Scale Formation Due to Water Spray)**



Photo Credit: Cummins Westport Inc.

**Figure 12: Photo of SLT2 Engine *Post Test* (Note the Scale Formation Due to Water Spray)**



Photo Credit: Cummins Westport Inc.

**Figure 13: Exhaust Manifold Crack on SLT2 Engine**



Photo Credit: Cummins Westport Inc.

**Figure 14: Turbine Housing Crack on SLT2 Engine**

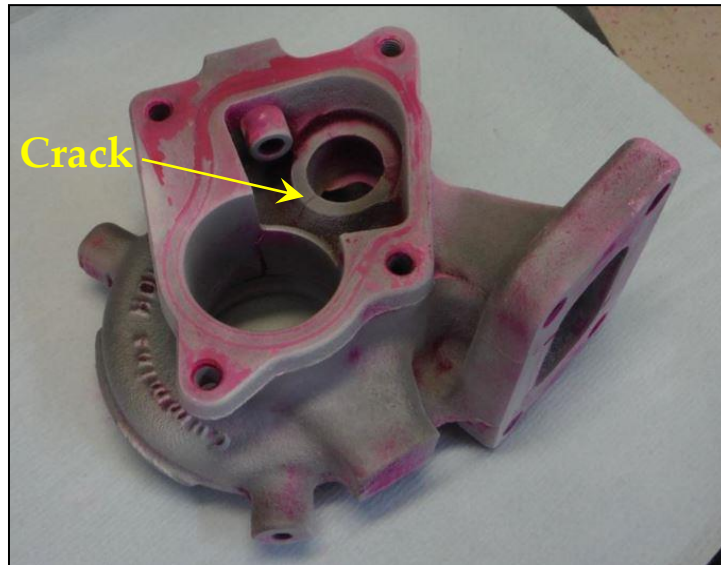


Photo Credit: Cummins Westport Inc.

**Figure 15: Photo of Combustion Face (No Cracks Present)**

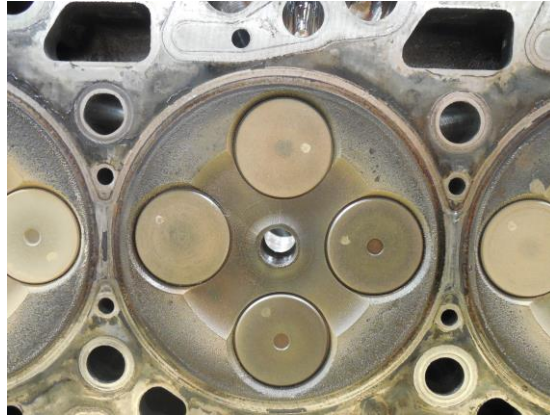


Photo Credit: Cummins Westport Inc.

**Figure 16: Photo of Combustion Face (UV Crack Detection — No Cracks Present)**



Photo Credit: Cummins Westport Inc.

SLT3 — Urban Bus Duty Cycle. This test is a 500 hour highly transient, light-duty cycle test as might be seen on an urban bus application. The test is broken into 3 sections. The first part of the test runs for 250 hours with load (simulating maximum vehicle curb weight). The second section runs for 50 hours without load (simulating minimum vehicle curb weight). The final 200 hours runs under the same loading as the first part of the tests. Note also that there are some periods of extended idle. See Figure 17 and Figure 18, which illustrate the speed versus load cycle of the test.

**Figure 17: SLT3 Duty Cycle Plot – Loaded**

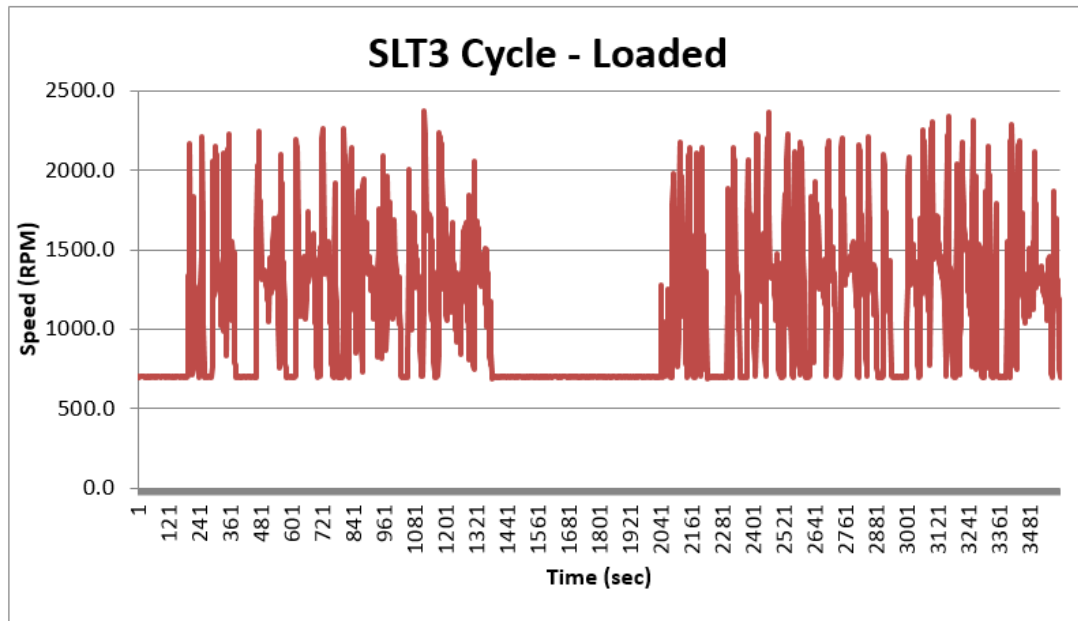


Photo Credit: Cummins Westport Inc.

**Figure 18: SLT3 Duty Cycle Plot – Unloaded**

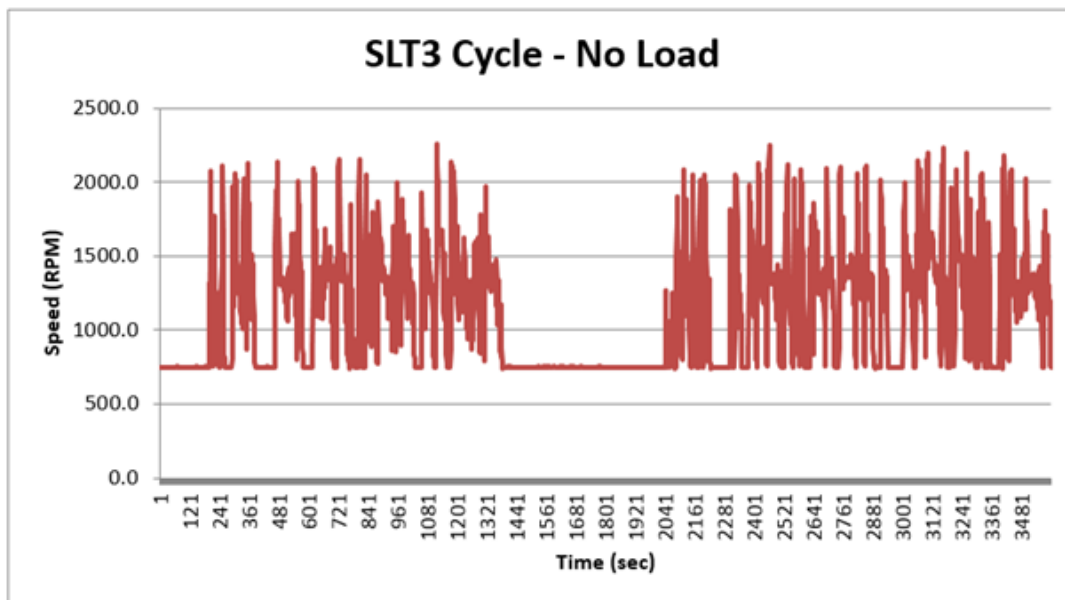


Photo Credit: Cummins Westport Inc.

Result of SLT3. The overall result is a pass with follow-on specific issues. Engine condition at the end of the test was generally noted as “like new, gently worn.” Notable in the engine was the presence of rust near the top of cylinder bore #3. The issue is being tracked through the Cummins FIRG process.

Hot Box – Overheat Simulation. This test is designed to validate the engine robustness with respect to overheat. The test runs at rated power for 250 hours with hot intake air and hot coolant. The test ignores engine protection protocol, which leads to conditions that far exceed what is expected to be seen in normal operation.

Result of Hot Box. The overall result is a pass with follow-on specific issues. Engine condition at the end of the test was generally noted as “like new, gently worn”. Notable in the engine was the presence of rust near the top of several cylinder bores. The issue is being tracked through the Cummins FIRG process.

Over Torque (Fuel) Test –This test is a 500 hour standard endurance test with the exception of having increased power (approximately 10 percent). This test is designed primarily to validate the power cylinder robustness.

Result of Over Torque (Fuel) Test. The overall result is a pass with follow-on specific issues. Engine condition at the end of the test was generally noted as “like new, gently worn”. There were no issues from the test that require follow-up using the Cummins FIRG process.

Cycle Six Test – This test is a 1000 hour cyclic endurance test with a cycle very similar to an emission DF test cycle, and is run under normal conditions (normal coolant and air temperature).

Result of the Cycle Six Test. The overall result is a pass with several minor issues. Engine condition at the end of the test was generally noted as “like new, gently worn”. Notable in the engine was the presence of rust near the top of several cylinder bores. The issue is being tracked through the Cummins FIRG process.

Short Hour and Mapping tests. In addition to the bigger more complex SLT tests, there are a number of important shorter tests that are worth mentioning. These activities, also called *mapping*, are important to the validation process. Table 5 lists some (not all) of the mapping tests run on the ISB6.7 G during the Alpha phase of the project.

**Table 5: Listing of Short Hour Testing and Results**

Test	Purpose (To verify...)	Outcome
Engine Valve & Seat Temperature	Material selection	Material selection confirmed. No Changes.
Water Pump Verification	Coolant flow rate and cavitation margin	Flows and margin confirmed. No Changes.
Emulsion Test	Emulsion characteristics and to verify CCV solution for emulsion reduction	Emulsion is seen mostly in CCV filter. Heated filter will significantly reduce the formation of emulsion.
Vibration Mapping	Vibration levels on critical components (fuel module, ignition module, engine control module, valve cover)	Vibration levels measured and actions taken on fuel module and ignition module.
Pin Joint Seizure	Pin joint design/fit is robust	Passed without issue.
Piston Temperature	Piston limits are not exceeded	Work is being done in December 2014. Previous testing indicates no issues, but testing is beneficial on many levels.

Photo Credit: Cummins Westport Inc.

### 3.1.2 Vehicle Testing and Verification

A significant amount of vehicle testing has taken place with the ISB6.7G engine to validate requirements. Starting in early 2014, many miles and hours of testing have been logged and are summarized below.

#### 3.1.2.1 Engineering Vehicles

Early in 2014, our first test vehicle was running with a pre-Alpha engine. The truck was used for preliminary control and transmission tuning, as well as turbocharger duty cycle measurement.

In summer of 2014, a team of engineers traveled to the Western United States to test an engineering vehicle in both high-altitude and very hot conditions. The first leg of the trip was to Colorado. There, the team conducted seven days of testing both in Denver and at higher altitudes. Several issues were discovered:

- Intake manifold temperature algorithm was not tuned, which caused unnecessary faults.
- Minor misfire events were recorded (and could be “felt”) while driving. Team inspection of engine components found an EGR pressure sensor leak and repaired it.
- Turbocharger wheel speed estimator accuracy was found to be unacceptable and was re-tuned during the trip.

For the second phase of the trip, the team traveled to Las Vegas, Nevada. From there, day trips were taken into the desert to assess the engine’s response to very hot ambient conditions. During the trip, ambient temperature ranged from 99°F (37.22°C) to 114°F (45.56°C).

During the hot day trips, the following items were noted:

- Oil temperature was near our target limits, but was not as hot as anticipated. Measurements indicate an approximate 20°F (11.11°C) reduction 'in-chassis' as compared to the dyno test cell under hot box conditions.
- Engine power was acceptable at altitude with fan 'off'. However, with fan 'on', fan load was much higher than anticipated and fan management was not optimized resulting in a noticeable loss in power.

In August, the engineering vehicles were utilized to conduct a series of drive-by tests at the Cummins noise facility. With a few minor tweaks to the high-speed governor, both trucks (one automatic and one manual) passed the drive-by test.

#### *3.1.2.2 Field Testing*

In the spring of 2014, the team dedicated one of the engineering test vehicles to be used for a preliminary field test. The unit was driven on a local route in Columbus, Indiana. Over the two months of the test, the vehicle accumulated in excess of 2000 miles. Several issues were identified and are being resolved using the Cummins FIRG process. The test was terminated upon receipt of proper Alpha engines and commencement of Alpha field testing.

Alpha engines were built starting in May of 2014. The first engines built were allocated to performance and mechanical development. Those engines were used to prepare the calibrations and controls for field tests commencing in the summer of 2014. Field and OEM integration engines followed and were built in June 2014.

The field test team started the installation process during the third quarter (3Q) of 2014 and has been busy conducting installations and troubleshooting. Table 6 summarizes the actual field tests that are running using the ISB6.7G engine (as of December 2014). Note that many of field tests have not yet started, but are in the project plan. There is an aggressive plan to install those engines in early 2015.

**Table 6: Listing of ISB6.7 G Field Tests and Status**

Unit	Customer Detail	Rating	Application	Miles	Hours
1	Blue Water Transit	250 HP	Transit / Shuttle	5856	520
2	Blue Water Transit	250 HP	Transit / Shuttle	0	0
3	Kwik Trip Stores	260 HP	Delivery Truck	4844	142
4	Kwik Trip Stores	260 HP	Delivery Truck	13629	425
5	Ryder Rental	240 HP	MD Truck	36	26
6	Walmart	200 HP	Yard Spotter	1424	267
7	Penske Rental	260 HP	MD Truck	0	0
8	Penske Rental	260 HP	MD Truck	0	0
9	Penske Rental	260 HP	MD Truck	0	0
10	City of Irvine	200 HP	Sweeper	0	0
11	Dina Bus	250 HP	Transit / Shuttle	0	0
Cummins Westport Sponsored ("Real World Testing" Local to Columbus, IN)					
12	Kenworth T440	260 HP	MD Truck	0	0
13	Kenworth T440	260 HP	MD Truck	0	0
14	Freightliner M2	260 HP	MD Truck	0	0
15	Thomasbilt School Bus	220 HP	School Bus	0	0

Photo Credit: Cummins Westport Inc.

As can be seen in Table 6, the first five field test units were installed, tuned, and released into service and are accumulating miles. Several of the field units required a degree of troubleshooting and tuning prior to service release. Examples of issues experienced throughout the process include: idle instability, poor throttle response, false misfire detection, and airflow calculation errors. Nearly all of the issues have been resolved. None of the lingering issues have prevented the team from initiating testing.

**The geographical location of field tests and the application for each unit are shown in Figure 19. Photos of many of the planned field test applications are shown in**

Figure .



**Figure 19: Geographical Information of Alpha Field Test Sites**

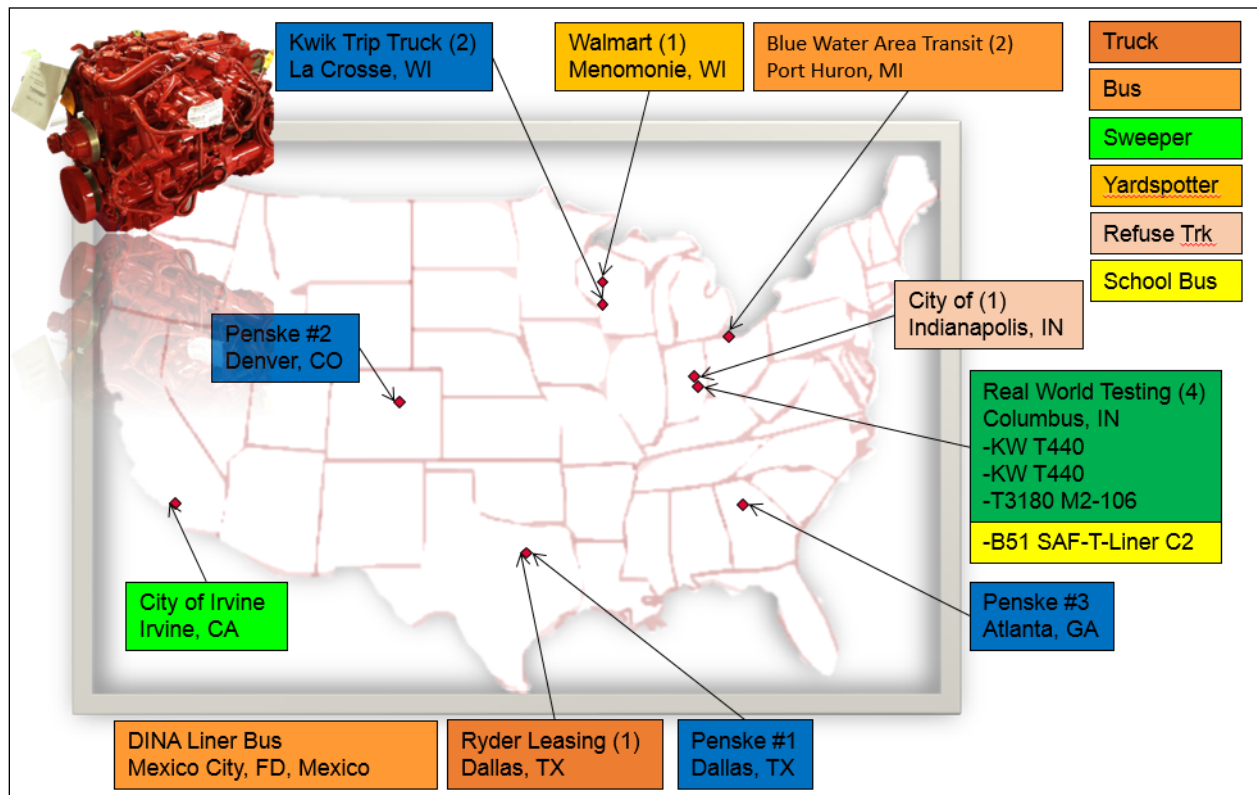


Photo Credit: Cummins Westport Inc.

**Figure 20: Photos of Field Test Chassis Platforms**



Photo Credit: Cummins Westport Inc.

### 3.1.3 Preliminary OEM Integration

Cummins Westport had been working with key customers to understand requirements for operation and installation. Over that last year, several of key customers completed CAD installation checks and provided feedback to allow CWI to design components that fit within the identified vehicles. In addition, shared performance data allows the OEM to specify a cooling system and transmission that will be suitable with the engine. The data sheets have been created and are in the process of being published on CWI's website, where, along with CAD models, all OEM's can access critical information and begin engineering the planned engine product into their vehicles.

## 3.2 Software and Calibration Development

Significant progress has been made in calibration development for the ISB6.7G. The following is a summary of accomplishments on calibration development:

- Cummins Insite™ tool has been released and is being used to manage field units on the program. The ISB6.7G has its own product ID. 70 percent of Insite features have been validated.
- In conjunction with Customer Engineering, all customer software features have been identified. As of December 2014, 70 percent of such features have been validated.
- Failure Mode Effects Test (FMET) is completed.
- NDOT (torque/acceleration controller) tuning complete for Alpha level engines, along with speed governor tuning on engineering vehicles.
- 80 percent of EMD+ required diagnostics are validated on engineering vehicle.
- Transmissions tuning of Allison 2500 & 3000 series was conducted for field test readiness.

The balance of work not finished will be completed in the first half of 2015 as we prepare for the Beta phase of the program

## 3.3 Combustion, Performance, and Emissions (CPE) Development

### 3.3.1 CPE Development Tasks Summary

A significant amount of combustion, performance, and emissions development work has been completed in this ISB6.7G project. Task 4 work focuses on the validation of engine performance and the preparation and delivery of calibrations for mechanical and field validation work.

Below is a summary of the activities that have been completed:

- All technical requirements were identified during the early phases of the program and work to confirm achievability was conducted during Task 4 (see Table 4, above for critical performance deliverables status).
- EGR tuning.

- Turbocharger wheel speed assessment and engine protection.
- Turbocharger wastegate operation and tuning.
- Limited space modeling was used to define spark timing constraints with respect to misfire, knock, and turbine inlet temperature limits.
- Preliminary emission tuning and verification using ‘production like’ catalyst. Testing demonstrated emission capability with the three-way catalyst used on the ISLG engine.
- Performance specifications, including heat rejection measurements, were released to critical partners in the development process.
- End-of-Line tests with pass-fail criteria were developed for use at the engine assembly plant in Rocky Mount, North Carolina. The End-of-line test was used for Alpha engines built in May 2014.

As previously shown in **Error! Reference source not found.**, a family of torque curves (ratings) or the ISB6.7G product was developed.

### 3.3.2 CPE Fuel Economy Comparison Summary

Cummins Vehicle Mission Simulation (VMS) software is used to estimate duty cycle fuel consumption of the ISB6.7G and comparing to other gas and diesel engines. VMS is the value-based analysis tool used by marketing, sales, and product engineering to simulate vehicle missions quickly and to gauge, communicate, and improve the value proposition of Cummins engines to customers.

Below there are two tables (Table 7 and Table 8) which show data from early VMS runs for the ISB6.7G compared to the B5.9 Gas Plus and 2013 ISB diesel product. As can be seen in the tables, our initial simulations show that the ISB6.7G is significantly more fuel efficient than the B5.9 Gas product. It should be noted that, given the age of the benchmark B-Gas engine product, a direct comparison is very difficult to verify. Nevertheless, the ISB6.7G is also well within the target of being no more than 15 percent less efficient than the diesel equivalent.

**Table 7: Vehicle Mission Simulation Comparison – ISB6.7 G vs. 2013 ISB Diesel**

<b>Engine Model</b>	<b>Peak Torque (lb-ft @ rpm)</b>	<b>Make / Model</b>	<b>VMS Route</b>	<b>GVW</b>	<b>Average % Difference in Fuel Economy for Gas as compared to 2013 Diesel (%)</b>
ISB 260	660 @ 1600	Medium Conventional	Urban Delivery	12000	-10.8
ISB 260	660 @ 1600	Medium Conventional	Urban Delivery	17000	-9.8
ISB 260	660 @ 1600	Medium Conventional	Urban Delivery	22000	-9.0
ISB 260	660 @ 1600	Medium Conventional	Urban Delivery	27000	-7.8
ISB 260	660 @ 1600	Medium Conventional	Urban Delivery	32000	-7.1
ISB 300	660 @ 1600	Medium Conventional	Rural Delivery	22000	-5.5
ISB 300	660 @ 1600	Medium Conventional	Rural Delivery	29500	-4.7
ISB 300	660 @ 1600	Medium Conventional	Rural Delivery	33000	-4.3

Photo Credit: Cummins Westport Inc.

**Table 8: Vehicle Mission Simulation Comparison – ISB6.7 G vs. 2002 B Gas Plus**

<b>Engine Model</b>	<b>Peak Torque (lb-ft @ rpm)</b>	<b>Make / Model</b>	<b>VMS Route</b>	<b>GVW</b>	<b>Average % Difference in Fuel Economy for ISB6.7 G as compare to 2002 BG+ (%)</b>
ISB 260	660 @ 1600	Medium Conventional	Rural Delivery	26000	19.0
ISB 260	660 @ 1600	School Bus	Urban Delivery	26000	12.4
ISB 260	660 @ 1600	Shuttle Bus	Intercity Delivery	26000	16.4

Photo Credit: Cummins Westport Inc.

## 3.4 Preliminary Beta Engine Design and Testing

### 3.4.1 Design Changes for Beta Engines

Several design changes are planned as summarized below:

- The wire harness design is changing to improve fit and to accommodate several design changes to the engine. The only functional change to the harness is the addition of an

exhaust manifold pressure sensor to be used for diagnosing misfire. All other changes are 'fit' related.

- The fuel module is being modified to:
  - Improve the manufacturability of the EGR delta P cross drillings.
  - Modify the intake manifold casting to accept a new 'rubber coated' steel gasket design.
  - Modify the air inlet connection geometry such that water will not stand next to the throttle plate, thus eliminating risk of ice formation and subsequent freezing of the throttle position.
- The valve cover is being converted from a sand casting to high pressure die casting. This is being done to reduce cost and weight of the cover. This will allow the cover to behave very similar to the diesel cover with respect to vibration and will reduce the risk of valve cover gasket leakage.
- The exhaust manifold is being modified to:
  - Solve a flange cracking issue discovered on the SLT2 test (see Figure 13).
  - Add a boss that will house a tube that will sense exhaust manifold pressure.
- A pressure sensor and a pressure sensor tube are being added to allow for better misfire detection (see Figure 21).

**The turbocharger is being modified to correct a crack discovered on the SLT2 test (see**

- **Figure ).** This change will affect the turbine housing. In addition, there will be a new wastegate setting pressure for Beta. The change to the setting will improve fuel economy slightly.

**Figure 21: ISB6.7 G Exhaust Manifold Pressure Sensor Tube**

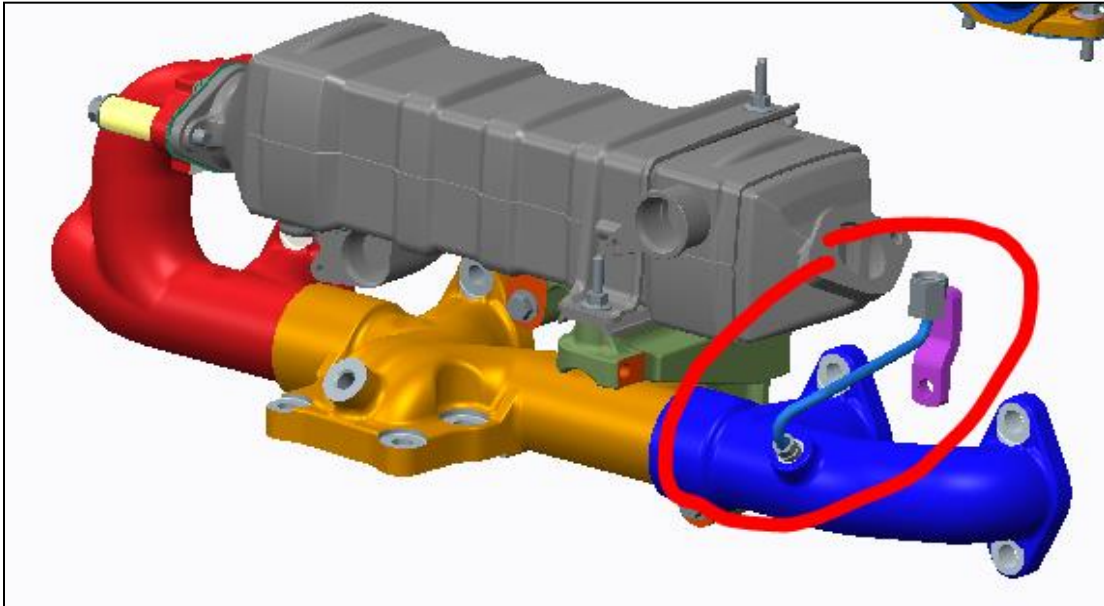


Photo Credit: Cummins Westport Inc.

### 3.4.2 Performance Calibration Work for Beta Engines

The following performance related work will be completed for Beta engines in 2015:

- Optimization of issues and concerns discovered late in the process of Alpha development.
- Development of a misfire diagnostic using exhaust manifold pressure measurements
- Cold weather testing in January 2015 (includes throttle function, throttle snaps, and startup).
- Hot weather and high altitude testing to ensure that recent calibrations are tuned and ready for production.

Emission certification will be conducted in late 2015 and will likely carry over into January 2016.

### 3.4.3 Field Test Plans for Beta Engines

In 2016, there will be multiple Alpha field tests installed as mention above in 2.2.2. In addition to the Alpha field tests, there will also be significant effort expended in deploying approximately nine additional Beta field tests. The customers for those field tests have not yet been identified.

## **CHAPTER 4:**

### **Task 5 – Data Collection Plan**

The data collection and analysis phase collects operational data and analyze the data for economic and environmental impacts. The key aspects of this task include:

- Development of a data collection test plan encompassing:
  - Fuel economy improvements
  - Greenhouse gas reductions
  - Air quality emission reductions
- Provide data on potential job creation, market potential, economic development, and increased state revenue as a result of expected future expansion.
- Provide an estimate of the project's energy savings and other benefits and potential statewide energy savings once market potential is realized.
- Comparison of project performance and expectations provided in the proposal with actual project performance and accomplishments.

#### **4.1 Data Collection Test Plan**

The Data Collection Test plan (Table 9) targeted the alpha production intent engines in test cell operation with subsequent simulation and analysis. Test cell operation offers the key advantages of isolating the engine from vehicle effects, and therefore, provides a more controlled environment to conduct repeatable tests that have been conducted on previous versions of this engine and other engines.

The goal is to capture data that will identify:

- Energy savings in terms of fuel economy (miles per diesel gallon equivalent). The engine is operated in a test cell and run at all engine speed and load combinations to determine a fuel map. This fuel map can then be used in subsequent analysis to estimate fuel economy in various drive cycles and load conditions.
- Tailpipe emissions including regulated air quality emissions, such as Particulate Matter (PM), Nitrogen Oxides (NO<sub>x</sub>), Carbon Monoxide (CO), Hydrocarbons (HC) and also greenhouse gases, such as Carbon Dioxide (CO<sub>2</sub>), Methane (CH<sub>4</sub>).

**Table 9: Data Collection Test Plan**

Test Subject	Test Method	Measurements Obtained
Fuel Consumption	Engine dynamometer	Fuel map determined at all engine load and speeds.
Fuel Efficiency	Cummins Vehicle Mission Simulation Analytical Model	Fuel Efficiency estimate for Class 5 to 7 vehicle drive cycles including: -Truck -School Bus
Air Quality Emissions	Engine dynamometer operated over FTP and RMCSET test cycles	NMHC NO <sub>x</sub> CO PM
Greenhouse Gas Emissions	Engine dynamometer operated over FTP and RMCSET test cycles	CO <sub>2</sub> N <sub>2</sub> O CH <sub>4</sub>

Photo Credit: Cummins Westport Inc.

## 4.2 Fuel Economy

Cummins Westport's objective for this project is to improve on the fuel economy of the CWI 5.9 liter lean burn spark ignition natural gas engine called the B Gas Plus by 5 percent to 10 percent. The B Gas Plus was sold in the North American market through 2009. This fuel economy assessment is conducted using specific Class 5 through 7 vehicle drive cycles including truck and school bus duty cycles.

Cummins Westport has mapped the fuel consumption of the 6.7 liter engine throughout the engine speed and load operating range during engine dynamometer testing. Cummins Westport Engineering then loaded these fuel maps into the Cummins vehicle mission simulation analytical model, which is used to predict vehicle fuel consumption and fuel economy based on specific vehicle, load, route, and load factor input data. Previously recorded CWI 5.9 liter lean burn spark ignition engine fuel maps were also loaded into the Cummins vehicle mission simulation model. This modeling was conducted for a variety of simulated Class 5 through 7 vehicle drive cycles, including truck and school bus duty cycles. This analysis concluded that the fuel consumption of the 6.7 liter natural gas engine ranges from 12 percent to 18 percent better than the B Gas Plus engine in the same duty cycles, and therefore, well exceeds the program target.

## 4.3 Greenhouse Gas Reductions

Natural gas offers significant GHG benefits versus petroleum fuels, as documented in ARB's low carbon fuel standard analysis. Table 10 summarizes the full-fuel cycle, or *well-to-wheel*, GHG emissions of ultra-low sulfur diesel fuel (ULSD) along with compressed natural gas



(CNG) and liquefied natural gas (LNG) from a variety of conventional and renewable fuel sources<sup>1</sup>.

**Table 10: Summary of ARB Low Carbon Fuel Standard Analysis**

<b>Fuel</b>	<b>Fuel Pathway</b>	<b>Well-to-Wheel Emissions (g CO<sub>2</sub>e/MJ)</b>	<b>% GHG Reduction vs. ULSD</b>	<b>Date of ARB Analysis</b>	<b>Version</b>
ULSD	California ULSD	98.0	-	12-Sep-12	Supplement to Version 2.1
<b>Conventional Natural Gas Pathways</b>					
CNG	North America NG	68.0	30.6%	27-Feb-09	Ver 2.1
<b>Renewable Natural Gas Pathways</b>					
CNG	Landfill Gas	11.3	88.5%	27-Feb-09	Ver 2.1
CNG	Dairy Digester Biogas	13.5	86.3%	20-Jul-09	Ver 1.0

Photo Credit: Cummins Westport Inc.

Cummins Westport has used the ARB analysis to forecast the GHG reductions associated with vehicles powered by the 6.7 liter natural gas engine. Based upon the ARB data in Table 10, and the assumptions listed in Table 11, full-fuel cycle GHG emissions were calculated, and are shown in Table 12 on a per vehicle per year basis.

Sample calculation:

25,000 miles per vehicle per year ÷ 8 mpg = 3,125 gallons per vehicle per year × 127,500 BTU per gallon = 398 MMBTU per vehicle per year × 1055 = 420,352 MJ per vehicle per year

3420,352 MJ per truck per year × 98.0 g CO<sub>2</sub>e / MJ (from Table 4) = 41.2 × 10<sup>6</sup> grams CO<sub>2</sub>e per vehicle per year.

**Table 11: Assumptions for Per Vehicle Emissions Calculations**

<b>Assumption:</b>	<b>Truck</b>	<b>School Bus</b>	<b>Units</b>
Average Annual Mileage for Target Market	25,000	15,000	miles/vehicle/year
Average Fuel Economy for Diesel Vehicle in Target Market	8	9	miles / gallon
6.7 Liter Engine Fuel Economy Differential vs. Diesel	5%	9%	less than diesel
Diesel Fuel Energy Content	127,500		LHV BTU/gallon
Joules per BTU	1055		

Photo Credit: Cummins Westport Inc.

<sup>1</sup> Cummins Westport summary of ARB GHG analysis: <http://www.arb.ca.gov/fuels/lcfs/lcfs.htm>

**Table 12: Annual GHG Emissions per Vehicle**

Fuel Type	Vehicle Use	Fuel Consumption (Gal or Diesel Gallon Equivalent /vehicle/yr)	Energy Content of Fuel (mmBTU/vehicle/yr)	Energy Content of Fuel (MJ/vehicle/yr)	GHG Emissions (Mg CO <sub>2</sub> e/vehicle/yr)	GHG Reduction vs. Diesel
Diesel (ULSD)	Truck	3,125	398	420,352	41.2	-
	School Bus	1,667	213	224,188	22	-
CNG (conventional fuel pathway)	Truck	3,289	419	442,475	30.1	27.0%
	School Bus	1,832	234	246,360	16.8	23.8%
CNG (landfill gas)	Truck	3,289	419	442,475	5.0	87.9%
	School Bus	1,832	234	246,360	2.8	87.4%
CNG (digester gas)	Truck	3,289	419	442,475	6.0	85.6%
	School Bus	1,832	234	246,360	3.3	84.9%

Photo Credit: Cummins Westport Inc.

The 6.7 liter natural gas engine will be capable of operating on either CNG or LNG, although most if not all applications are expected to use CNG. The ARB low carbon fuel standard full fuel cycle GHG emissions data summarized in Table 13 yields the following average GHG emissions for the various natural gas fuel pathways considered by ARB.

**Table 13: Average Full Fuel Cycle GHG Emissions for Various Fuel Pathways**

	Conventional Fuel Pathways	Renewable Fuel Pathways
Average GHG Emissions (Mg CO <sub>2</sub> e/vehicle/year)	23.4	4.3

Photo Credit: Cummins Westport Inc.

For example, based on the values in Table 12, the average GHG emissions corresponding to conventional fuel pathways is calculated as follows:

$$\text{Average GHG emissions} = (30.1 + 16.8) \div 2 = 23.4 \text{ Mg CO}_2\text{e per vehicle per year}$$

For the purpose of calculating total GHG emissions, Cummins Westport has identified a *base case* for natural gas fuel supply, assuming that 90 percent of the natural gas fuel consumed by the 6.7 liter natural gas –powered fleet will be derived from conventional natural gas fuel pathways, and 10 percent from bio-methane pathways. Cummins Westport has also identified

an *upside case*, which assumes that 50 percent of the fuel consumed by the fleet will be derived from bio-methane pathways. Table 14 quantifies the anticipated full-fuel cycle GHG emissions for trucks powered by the 6.7 liter natural gas engine, as a function of fuel source.

**Table 14: Average Full Fuel Cycle GHG Emissions with Varying Renewable Fuel Content**

	<b>Base Case (10% Renewable Fuel)</b>	<b>Upside Case (50% Renewable Fuel)</b>
Average GHG Emissions (Mg CO <sub>2</sub> e/vehicle/year)	21.5	13.8

Photo Credit: Cummins Westport Inc.

For example, the average GHG emissions corresponding to the base case fuel supply is calculated as follows, based on the values in Table 13:

$$\text{Average GHG emissions} = 23.4 \times 0.9 + 4.3 \times 0.1 = 21.5 \text{ Mg CO}_2\text{e / vehicle / year}$$

Table 15 summarizes the predicted full fuel cycle GHG benefits for the 6.7 liter natural gas engine versus diesel-powered Class 5 to 7 vehicles.

**Table 15: Predicted Full Fuel Cycle GHG Emissions Reductions vs. Diesel Vehicles**

	<b>Base Case (10% Renewable Fuel)</b>	<b>Upside Case (50% Renewable Fuel)</b>
Average GHG Emissions (Mg CO <sub>2</sub> e/vehicle/year)	31.9%	56.2%

Photo Credit: Cummins Westport Inc.

For example, the GHG emission reduction corresponding to the base case fuel supply is calculated as follows based on the values in Table 12 and Table 16:

$$\begin{aligned} \text{GHG emission reduction} &= (\text{Diesel emissions calculated by averaging of truck and bus values} - \\ &\quad \text{6.7 liter emissions}) / \text{Diesel emissions} \\ &= (31.6 - 21.5) \div 31.6 = 31.9\% \end{aligned}$$

U.S. EPA and the National Highway Transportation Safety Administration introduced new GHG and fuel consumption standards that came into effect for heavy-duty engines and vehicles in 2014. These regulations are not based on full-fuel cycle emissions; rather, they disregard all emissions produced prior to usage in the engine and vehicle, and are based on *tank-to-wheels* emissions. Cummins Westport intends to launch the 6.7 liter natural gas engine in compliance with the first phase of the U.S. EPA and National Highway Transportation Safety Administration regulations. Preliminary GHG emission data indicates that the 6.7 liter engine will achieve the first phase of GHG emission standards based on the current design, as shown previously shown in Table 3. Additional emission testing throughout the duration of the engine

development program is expected to confirm that the launch design will achieve the first phase of GHG regulations.

## 4.4 Criteria Pollutant Emissions

**The 6.7 liter engine will be certified to exceed U.S. EPA/ARB emission standards. Preliminary emission testing of the 6.7 liter engine indicates emissions below the standards as shown in**

Table 3. Further tuning will be done prior to product certification and launch.

## 4.5 Economic Benefit

The project is expected to address the shortage of natural gas products available to commercial vehicle markets in California and elsewhere, and to optimize the performance and fuel economy of spark-ignited natural gas engines in Class 3 through 7 truck and bus applications. By developing and subsequently commercializing a low emission, high performance, high efficiency 6.7 liter natural gas engine for these applications, a viable alternative to diesel engines currently serving this market will be made available. The natural gas engines currently available to serve these applications, consisting mostly of after-market conversions, are not considered optimized for fuel efficient performance. Accordingly, the natural gas ratepayers who purchase the proposed new 6.7 liter natural gas engines in the future are expected to directly benefit by cost savings per mile traveled. This higher efficiency will also reduce the emissions of criteria pollutants and GHGs per mile traveled.

Natural gas ratepayers will also benefit from reduced consumption of diesel fuel as the 6.7 liter natural gas engine displaces diesel in the target market application. Natural gas use will lessen petroleum imports used for affected markets. This reduced demand for diesel should enable gasoline production from capacity constrained refinery industry that may help mitigate volatility in gasoline prices.

GHG emissions and particulate matter from natural gas engines is lower compared to diesel engines. The magnitude of the GHG emission reductions enabled by ISB6.7 G-powered vehicles will increase considerably over time as renewable natural gas pathways comprise more of the California natural gas fuel mix.

Trucking is critical to the United States and California economy. Because of the trucking industry's importance to commerce and because of its large employment base, it is very important that environmentally responsive technologies are developed that enable the industry to remain a vital component of the State's economic future. Trucks haul 69 percent of all freight tonnage, and collect 84 cents of every dollar spent on domestic freight transportation. There are almost nine million people in trucking-related jobs, including over three million truck drivers. About 15 percent of trucking jobs are in manufacturing, in plants across North America. It should be noted that most trucks used in the United States are designed for the North American market, in contrast to the light-duty truck market. At present, there is very little competition from imported vehicles because of differing regulations and customer needs. This includes component suppliers such as CNG cylinder manufacturers like SCI and Luxfer (operating in California).

Commercial availability of the ISB6.7 G engine will be a key enabler of natural gas adoption in the Class 5 to 7 truck market as well as the school bus and shuttle bus markets, which in turn will significantly increase demand for natural gas fueling stations. Jobs will be created to build many more natural gas fueling stations, which in turn will create employment for component suppliers and trades-people. Note that Clean Energy Inc. (a California-based company) is the nation's leading provider of natural gas fueling station infrastructure. Increased natural gas demand, along with promotion and incentives for bio methane production, will create permanent jobs related to collection, treatment, dispensing, and distribution of bio methane for transportation purposes from renewable resources including landfills, dairies, and sewage treatment facilities. The biogas industry is in its infancy in North America and throughout the world; therefore, California's leadership position at developing this market is likely to enable California bio methane technology providers to replicate their products and services worldwide.

## **4.6 Energy Savings**

The 2011 Integrated Energy Policy Report<sup>2</sup> provides a summary of priority energy issues currently facing California. This project supports several key goals, initiatives, and demand scenarios in this report. One main goal is the displacement of petroleum in the transportation sector and this project supports two of the report's general strategies to this end; increasing fuel efficiency in the fleet of vehicles, engines, aircraft, and vessels, and using non-petroleum fuels. The report states:

Natural gas vehicles are an attractive alternative to medium- and heavy-duty fleet owners and operators who have concerns with the cost of diesel fuel resulting from price volatility and the economic downturn, as well as compliance with air quality standards. Additionally, natural gas vehicles have been shown to have GHG reductions of between 11 and 16 percent compared to their diesel counterparts. If using waste-derived bio methane instead of conventional natural gas, however, these vehicles can achieve GHG reductions of roughly 85 percent below diesel counterparts.

The engine platform developed in this project will be uniquely suited for Class 5 through 7 commercial vehicle markets because it will have the right attributes (displacement, weight, envelope size, and performance) to appeal to this broad customer base. It has the ability to operate with bio methane in blends or with 100 percent bio methane without modification of engine hardware or calibrations, provided that the fuel composition meets CWI's fuel specifications. The current fleet of medium and heavy-duty trucks in California is approximately 632,000 and with the release of the ISB6.7 G, along with the other natural gas engines developed by CWI, the majority of future vehicle acquisitions in this sector will have the opportunity to select natural gas instead of gasoline or diesel as a fuel source.

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<sup>2</sup> California Energy Commission, 2011. 2011 Integrated Energy Policy Report. Publication Number: CEC-100-2011-001-CMF

Another key initiative of the California Energy Policy supported by this project is energy security. The use of natural gas as a vehicle fuel directly leads to the energy security of California and the country. Two scenarios were established in the IEPR Report in respect to the potential of future alternative fuel use in the state and this engine assists in the goal of meeting the higher alternative fuel use path.

In respect to future energy policy, this engine platform will hopefully establish lower NO<sub>x</sub> certifications than ever considered before for internal combustion engines as well as having the potential to increase the displaced petroleum in the transportation sector above even the aforementioned high scenario.

## **4.7 Verification of Critical Engine Performance Targets**

The engine has specific critical performance deliverables that were verified early in the pre Alpha process and some again in the Alpha process. These targets are defined by gathering critical inputs from key customers in Voice of the Customer Interviews. Table 4 shows our targets and a result of our testing.

# **CHAPTER 5:**

## **Task 6 – Technology Transfer Activities**

### **5.1 Technology Transfer Plan**

All CWI product development projects follow the Cummins process for developing, validating, and commercializing new engines. It is a rigorous and comprehensive process addressing all areas to define, design, and develop the product for the market—including technical, manufacturing, purchasing, marketing, customer engineering, and customer care areas. The process is broken into various stages with pre-defined tasks to be completed before moving onto the next phase of development.

Within this product development structure are various engine design phases—including Concept, Pre-Alpha, Alpha, and Beta—Limited Production, and Production. The structure culminates with commercial launch of the Production engine design. The scope of this project carries the development of the ISB6.7 G engine through to the Alpha engine design, build, and validation testing. The Beta phase through to commercialization is not included in the scope of this project, but following the successful completion of the Alpha phase has been initiated.

A cross-functional team, or Core Team, is assembled with representation from each of the areas involved in the product development process. It is within this Core Team that the individual area development plans are pulled together to form the complete product development plan and a program schedule to ensure completeness and timeliness. A high-level program schedule for the ISB6.7 G program is shown in Figure . Throughout the development process the Core Team meets regularly to track the progress as well as identify challenges which need to be addressed through appropriate mitigating action ensuring potential consequences are controlled.

**Figure 22: ISB6.7 G Program Schedule**

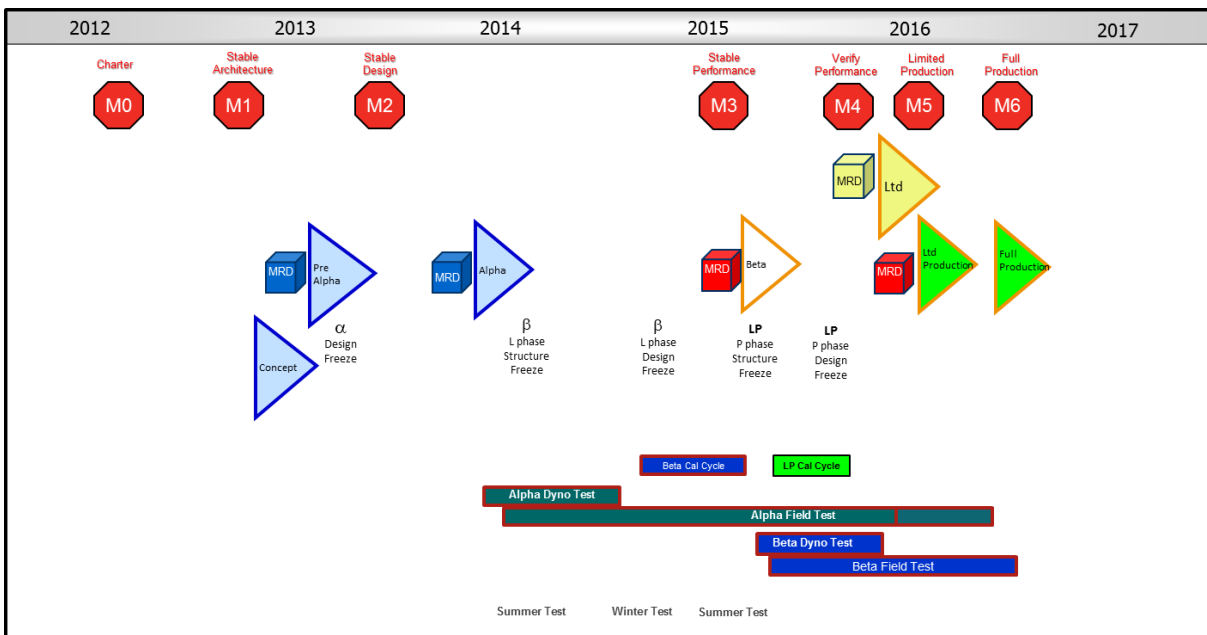


Photo Credit: Cummins Westport Inc.

At various stages and within various areas of this product development process, there are numerous tasks where the knowledge gained in this development process is transferred outside of CWI to the various external stakeholders and results in a commercial product available to the public. This product is expected to be capable of meeting customer requirements. A summary of the knowledge transfer is shown in Table 16.

These external stakeholders include the vehicle OEM's, such as Peterbilt, Kenworth, Freightliner, Thomas Built Bus, and so forth, that will offer the engine in their vehicles. Each of these vehicle OEM's already offers the Cummins ISB6.7 diesel engine, which makes the vehicle integration portion of the process easier but not trivial. These stakeholders are engaged by the Marketing and Customer Engineering groups at the start of the development process to understand the path to market and feed in the voice of the customer. As the development process progresses, continued interaction between CWI and the vehicle OEM's focuses on transferring newly gained information on the engine design, including the physical fit and interface of the engine as well as performance attributes.

The Customer Engineering group also provides Off-Engine Fuel System Integrators with engine fuel requirements to ensure the fuel is in the appropriate condition before entering the engine. This information is also shared with refueling station providers and the fuel providers to educate and ensure quality product is available to customer fleets to power these engines.

Towards the end of the technical development activities and prior to commercially launching the product, the Technical team submits the prescribed criteria pollutant and greenhouse gas emission test data to the respective government agencies, such as U.S. EPA and ARB, for engine



certification. The U.S. EPA and ARB then make this emission test data available to the public in the form of Certificates of Conformity and Executive Orders, respectively.

The Customer Care group develops the extensive service material—including repair manuals, parts lists, training materials, and so forth—and delivers these to the Cummins Distribution network and Cummins Service network throughout North America and internationally.

CWI marketing, in collaboration with Cummins marketing, develops the sales and marketing literature, advertisements, and promotional materials. There is heavy CWI and CMI presence at trade shows to promote and educate vehicle OEM's and fleets as well as government agencies on the technical aspects and benefits of the CWI engines.

**Table 16: CWI External Stakeholder Information Transfer Summary**

<b>CWI Core Team Area</b>	<b>Information Transferred</b>	<b>External Stakeholder</b>
Technical	Engine emission profiles	U.S. EPA & ARB
Manufacturing	Engine details, including comparison to existing engine products	Cummins Engine Plant
Purchasing	Part specifications Commercial details	Suppliers
Marketing	Product attributes in terms of Voice of Customer Marketing literature, advertisement, and promotional materials.	Vehicle OEM's Fleets Government Agencies
Customer Engineering	Engine performance details Torque & power curves Installation models & drawings Wiring drawings & interface Application Engineering Bulletins	Vehicle OEM's Cummins Distribution network Cummins Service network
	Engine fuel requirements	Off-engine fuel system integrators Refueling station providers Fuel providers
Customer Care	Maintenance schedules Repair manuals Replacement parts lists Training materials	Cummins Distributors Fleet Maintenance Departments

Photo Credit: Cummins Westport Inc.

## 5.2 Project End Users

Although this project does not result in the commercialization of the ISB6.7 G engine because there is still significant work required to bring this product to the market, the intended uses of the product is clearly identified.

CWI's target markets for the ISB6.7 G engine include the following applications and chassis platforms:

- School buses, particularly Type C (large, front-engine, conventional style buses with a hood and front fender assembly, with the entrance door located behind the front axle, and with seating capacity up to 77 passengers) and Type D (large flat front transit buses that are typically rear-engine with the entrance door located ahead of the front axle and with seating capacity up to 90 passengers).
- Medium-duty trucks, which are used in a variety of applications including pickup and delivery, food and beverage distribution, package delivery, municipal and utility work trucks, and so forth.
- Yard tractors, also known as yard spotters, yard hostlers, yard jockeys, yard goats, or terminal tractors.
- Shuttle buses, such as the ones used at airports.
- Specialized municipal works vehicles, such as street sweepers.

All of these vehicle applications are commonly used throughout California. California has over 21,000 school buses<sup>3</sup>, and more than 10 percent of all medium- and heavy-duty trucks in the nation are registered in California, which is more than any other state<sup>4</sup>.

Based on CWI's extensive discussions with OEMs and end-users in the target markets, as well as CWI's review of historical Cummins diesel engine sales data to North American OEMs, the dominant engine displacement node in the target markets is 6.7 liters, and the predominant power and torque ranges are 200 to 260 hp and 500 to 660 lb-ft torque. Therefore, the ISB6.7 G engine will have the right attributes (displacement, weight, envelope size, and performance) to appeal to many customers throughout the target markets.

The path to market for this product is through vehicle OEM's. Typically products are commercialized with Launch Partners initially and then subsequent partners and vehicle options are added post launch as the market and demand grows and resources become available. The Launch Partners planned for the ISB6.7 G cover the intended use of the product and are shown in Table 17.

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<sup>3</sup> <http://www.schoolbusfleet.com/files/stats/SBFFB13-stats-stateby-state.pdf>

<sup>4</sup> U.S. Census Bureau Vehicle Inventory and Use Survey, Table A:  
<http://www.census.gov/prod/ec02/ec02tv-us.pdf>

**Table 17: ISB6.7 G OEM Availability at Commercial Launch**

<b>OEM</b>	<b>Peterbilt</b>	<b>Kenworth</b>	<b>Freightliner</b>	<b>Thomas Built Bus</b>	<b>DINA</b>	<b>ADL / New Flyer</b>	<b>TICO</b>
Model	325, 330, 337, 348	T170, T270, T370	M2-106, 108SD	C2	Linner G, Picker G	MiDi E200	Pro-Spotter
Engine	ISB6.7 G	ISB6.7 G	ISB6.7 G	ISB6.7 G	ISB6.7 G	ISB6.7 G	ISB6.7 G
Application	Truck	Truck	Truck	School Bus	Shuttle Bus	Shuttle Bus	Yard Spotter
Availability	2016 Launch Partner	2016 Launch Partner	2016 Launch Partner	2016 Launch Partner	2016 Launch Partner	2016 Launch Partner	2016 Launch Partner

Photo Credit: Cummins Westport Inc.

# CHAPTER 6:

## Task 7 – Production Readiness Plan

### 6.1 Production Readiness

The ISB6.7 G production plan has always included manufacturing the product in the Cummins RMEP located in North Carolina (Figure 23). This facility is currently the production plant for the ISB, ISC, and ISL family of engine products serving a large number of applications worldwide. Most closely related to the ISB6.7 G are the ISB6.7 diesel and the ISL G natural gas engines, both produced at the RMEP facility.

**Figure 23: Rocky Mount Engine Plant (RMEP)**



Photo Credit: Cummins Westport Inc.

The manufacturing of the ISB6.7 G is a derivation of the existing ISB6.7 diesel and ISL G natural gas engine platforms manufactured at RMEP, and will utilize the existing assembly line in its entirety. The ISB6.7 G final assembly will start at the same point in the assembly line as the other products produced at RMEP, beginning with the installation of the crankshaft into the engine block. All manufacturing processes unique for natural gas production, previously created to facilitate the production of the ISL G, will be utilized for the production of the ISB6.7 G. There are no new requirements on the plant for manufacturing the ISB6.7 G related to safety, emissions compliance, assembly, or acceptance testing and shipping. Adding the ISB6.7 G is virtually transparent to the existing plant requirements, already in place for the ISL G and ISB6.7 diesel. Therefore, each installation station on the RMEP production line must be capable of accommodating diesel or NG engines without changing tooling or technicians.

The production plan for the ISB6.7 G has been developed based on a strategy that the assembly of the new engine will be integrated into an existing engine assembly line within the company.

An assessment has been made to identify the similarities and the differences between existing engine designs and the new engine design. The differences have driven process changes in the existing line (Figure 24). The manufacturing engineering personnel have worked with the design engineering personnel to minimize the differences and to optimize the design from a manufacturing perspective without compromising the integrity of the design.

**Figure 24: RMEP Production Assembly Line**



Photo Credit: Cummins Westport Inc.

A preliminary assembly process has been defined. The process has been tested by building approximately 32 engines as part of a prototype engine build event. Issues identified during this build have been logged and a joint effort between manufacturing engineering and design engineering is in process to resolve each issue. The proposed design changes identified during the Alpha engine build are being evaluated in an off-line build area (Figure 25) prior to being proven and validated in the main assembly process. A production process validation build (Beta) is planned for mid-2015 to ensure the build issues have been resolved and to identify any new build issues. RMEP Operations staff used the Alpha build to assess the cycle-time to complete ISB6.7 G-unique installations and then determined which installation station should perform each operation. This was done to ensure that the overall production line remained balanced and that no single installation station became the *choke point* for the production line during other engine model production.



**Figure 25: RMEP Off-Line Build Area**



Photo Credit: Cummins Westport Inc.

There is a change on the cylinder head machining line to accommodate the ISB6.7 G cylinder head. Since the ISB6.7 G is based on the ISB6.7 diesel version of the engine, it uses the same cylinder head casting as the diesel version, but needs to incorporate accommodations for spark plugs (one per cylinder). The original diesel cylinder head casting was used for the ISB7.6 G design to maintain the majority of machining process on the cylinder head machining line. This has been evaluated and a process has been defined using the current high volume machining line along with an off-line machining cell for new features. The cylinder head (machining and assembly) line creates finished cylinder head sub-assemblies that feed into the main engine assembly line. These are finished cylinder heads ready for assembly to the engine.

The new off-line cell includes a CNC machining center and a press machine to install valve seats. The cylinder heads will be machined through the first half of the existing machining line, then moved to the off-line cell for the unique features, and then returned to the existing machining line to complete the machining process. The CNC machine is flexible and able to address all the new features, but restricts the capacity due to the time to machine each part. Additional capacity can be added by duplicating the CNC machine with additional CNC machines in the cell. Based on the forecasted volume for the ISB6.7 G in its first six years of production, the single CNC machining center is capable of maintaining a steady supply of cylinder heads to meet production needs. If production volumes exceed the forecast, RMEP will be able to continue cylinder head machining and assembly on additional shifts to keep up with demand. RMEP also maintains an annual capital spending plan that takes into account procurement of additional machining center tooling should the production forecast outpace the existing machining and assembly capability. This plan includes options for increasing

machining and assembly output within and outside of the plant prior to acquiring additional flexible machining centers.

The new CNC machining center for the ISB6.7 G cylinder head has been validated on both the pre-Alpha and Alpha ISB6.7 G engine builds. This new machining center will be used for the upcoming Beta build in 2015 and then for full production in 2016 and beyond.

The business systems that are being used in the manufacturing plant are capable of integrating the new engine into the plant without changes or additions. Manning levels have been reviewed and it is expected that one additional operator per shift will be required to man the offline machining cell. Otherwise no additional head count will be required.

There are no additional requirements stemming from the production of the ISB6.7 G affecting RMEP's current process for the use of hazardous or non-recyclable materials. The plants current processes adequately support the ISB6.7 G production requirements and meet all Cummins manufacturing requirements and standards.

A preliminary ramp up plan has been defined that will begin with a limited production phase in 2016 and ramp up to full production levels by the end of 2016. Limited production will start exclusively for engines to be used in the school bus market and will be limited to the lower horsepower ratings (200HP and 220HP). This ramp up plan will begin in April of 2016 to accommodate the buying cycle for the school bus market. The production ramp will be coordinated with the school bus OEMs and engine production will be managed based on production quality. As end-of-line testing / inspection issues are minimized and quality targets are achieved, production volumes will be allowed to increase. The other vehicle markets, which include truck, shuttle bus, yard spotter, and street sweeper, will be phased into production early in the fourth quarter of 2016. This will include the higher horsepower ratings of 240HP and 250HP.

Throughout Task 7, the Cummins Purchasing group identified and validated production suppliers for all natural gas-unique components in the ISB6.7 G design. Greater than 80 percent of the individual components in the ISB6.7 G design are identical to the components used by Cummins for ISB6.7 diesel engine production. Of the remaining 20 percent, some parts are common with the ISL G. The components unique to ISB6.7 G include the cylinder head, pistons, turbo-charger, fuel module, ECM, ignition system, spark plugs, valve cover, and wire harness. For each of these unique components, the Purchasing group identified a production supplier with high volume production capability, then provided design specifications to the supplier. In many cases the production suppliers provided design input and feedback to optimize design for manufacturability and identified potential cost saving opportunities. In later stages of the program, the Purchasing groups (both in Columbus, IN and at RMEP) will work with suppliers to confirm high-volume production capability at negotiated cost targets, to ensure supplier adherence to CWI's component specifications, and to ensure that all suppliers were validated and approved in accordance with industry standard PPAP requirements (Production Part Approval Process). The PPAP process requires each supplier to produce a batch of components using production tooling and production processes, and to inspect each component to ensure

compliance with the specified manufacturing tolerances and performance criteria. All PPAP work continues to support final release of the unique hardware required for the limited production launch, which is scheduled to begin production in April of 2016. Long lead items such as exhaust manifold, wiring harness, and piston have had funding authorized for production tooling, so parts made from production tooling can be used for the Beta build validated through test cell and field testing in time for start of limited production.

In production, ISB6.7 G engines will be ordered electronically by OEMs using the Cummins On-Line Specifications (COLS) order entry process that Cummins employs for diesel engine orders. The COLS order entry system is linked to the component and options database that is maintained by Cummins and CWI Engineering, whereby individual components are categorized into various option groupings (such as engine block vs. cylinder head vs. turbo-charger vs. exhaust manifold vs. fuel filter and so on) Details of the ISB6.7 G option release status are described in the Task 4 - "Alpha Validation Testing and Preliminary Beta Design" report for this project. All Alpha engines were ordered via the COLS online order entry process, thus validating the order entry process prior to initiating commercial launch of the ISB6.7 G engine. The same process on line process using COLS order entry system will be used for the Beta engine orders as well.

**Figure 26: ISB6.7 G Alpha Engine Ready to Ship from RMEP**



Photo Credit: Cummins Westport Inc.



Cummins and Cummins Westport Application Engineers worked directly with vehicle OEMs to ensure the engine will fit in a wide range of OEM chassis models, and to ensure that each OEM's design meets CWI's installation requirements and recommendations, such as electrical interface specifications, engine coolant and charge air cooling capability, and correct sizing and routing of fuel delivery hoses. Throughout Task 7, CWI worked with a several truck OEMs including Freightliner, Kenworth, Peterbilt, Thomas Built Bus, Dina, ADL / New Flyer, and TICO. The Application Engineers provided each OEM with CAD models for the Alpha and Beta engines. The Beta engine design incorporated feedback from the OEMs to optimize the engine fit in their respective truck chassis. The team has effectively worked with all OEM launch partners in efforts to minimize proliferation of engine options and standardize on an engine configuration that requires few option changes between OEM chassis variations. The OEM launch partners along with the application and chassis model(s) are shown previously in Table 17.

The ISB6.7 G Alpha engine build was conducted in Q2 2014 and involved 38 engines. The OEMs continued to provide installation feedback and design change requests based on their Alpha installation experience. CWI incorporated that feedback into a final design iteration and a Beta engine build is planned for July 2015. CWI conducted the Alpha build to validate all production processes including order entry, RMEP production processes, and hot-test. The Alpha engines were delivered to truck OEMs to validate each OEM's production readiness in their truck assembly plants (Figure 27). Beta engines will be used for the same purpose. The Beta build will consist of an estimated 20 engines built and tested at RMEP using production processes to further validate production readiness

**Figure 27: ISB6.7 G Alpha Engine Installed in Thomas Bus C2 Chassis**



Photo Credit: Cummins Westport Inc.

The truck OEMs used ISB6.7 G Alpha and will use Beta engines to complete the final testing to validate that their engine installations meet their design specifications and also satisfy CWI's engine installation requirements and recommendations. Prior to production launch, CWI and the OEMs completed the Cummins installation quality assurance process, whereby the OEMs provide extensive data and design specifications documenting the engine installation in each vehicle model, along with data demonstrating compliance with critical vehicle performance requirements such as the ability to accommodate the engine coolant and charge air heat rejection rates with the engine operating at rated power in high ambient temperatures.

# CHAPTER 7:

## Conclusion and Recommendations

### 7.1 Conclusion

As part of the agreement, the research team sought to:

- Design, develop, and demonstrate (on dynamometer) an Alpha stage 6.7 liter medium duty natural gas engine that can be certified at or below U.S. EPA / ARB 2013 emission standards (g/bhp-hr): 0.20 NO<sub>x</sub>, 0.14 NMHC, 0.01 PM, 15.5 CO
- Demonstrate a peak rating of 260 hp and 660 lbs-ft. peak torque
- Improve fuel economy by 5 percent to 10 percent when compared to CWI's 5.9 liter lean burn spark ignition natural gas engine that CWI sold in the North American market through 2009. This assessment will be measured by analyzing fuel maps over specific Class 5 through 7 truck and school bus duty cycles.
- Demonstrate GHG emissions (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) that will enable emission certification at or below the U.S. EPA 2017 GHG emission standards

All of the aforementioned objectives have been achieved in this project. CWI decided to base the new natural gas engine development on the new ISB 2013 diesel engine platform and refer to the natural gas engine as the ISB6.7 G engine.

The pre-Alpha phase of the development process defined and verified the engine architecture. Through analytical models and calculations and via dynamometer testing, initial verification of performance targets were achieved. The learning gained from the pre-Alpha engine operation was used to optimize and create a production intent engine and engine component designs.

A number of Alpha engines were built at the Rocky Mount Engine Plant utilizing the production assembly line and utilized in both engineering test cells and installed in vehicles for further real world testing. These Alpha engines were used to further assess the design capability to meet key performance targets gathered from Voice of the Customer interviews, ESW (Engineering Standard Work) standards, and past experience with other Cummins Westport and Cummins Diesel products. Preliminary emission, fuel consumption, and GHG data from the test cells shows that the engine design achieves the design targets for the program. CWI is continuing additional development work to further validate the engine design in preparation for emission certification and commercial launch.

This Energy Commission-sponsored project has ended with the Alpha engine design, build, and validation testing. The Beta phase through to commercialization is not included in the scope of this sponsored project, but it is underway and will continue into 2016. CWI has followed the Cummins' process for developing, validating, and commercializing new engines. This process brings together a cross-functional Core Team with defined tasks during each phase of the development. From the start of the development process and through to the commercialization of the product, CWI has engaged external stakeholders including Cummins Distribution and

Service networks, Government agencies such as U.S. EPA and ARB, and fleets to transfer the knowledge gained, experimental results, and lessons learned. All OEM launch partners are committed and have either validated their installations using Alpha engines or will do so using Beta engines. All OEMs will be required to comply with Cummins installation quality assurance requirements prior to approval for receiving production engine shipments, to insure quality

The RMEP facility is currently in production with both the ISL G and ISB6.7 diesel products (parent products). ISB6.7 G is a streamlined addition to the current production line, requiring very few process changes from those of the ISB6.7 diesel or the ISL G. The Beta engine build will continue into 2016 and will be comprised of greater than 80 percent production parts. New tooling for the ISB6.7 G cylinder head has been validated on the Alpha build engines and will be further validated on the upcoming Beta engine build prior to full production.

## **7.2 Recommendations**

CWI recommends proceeding with the next stage of the overall ISB6.7 G engine development, demonstration, and commercialization, which will include the following activities:

- Field demonstrations with end-user customers to demonstrate engine reliability and durability, and to establish appropriate scheduled maintenance intervals.
- Calibration development and optimization to achieve program fuel economy targets.
- Continued accelerated testing to demonstrate component, sub-system, and engine durability.
- Volume-manufacturing of ISB6.7 G engines via scheduled Beta builds at RMEP
- Emission certification testing, including demonstrating emission durability over the U.S. EPA / ARB-prescribed useful life for medium-heavy duty engines.
- Vehicle integration activities with Class 5 to 7 vehicle manufacturers, including installation quality assurance reviews to ensure that all engine installation requirements and recommendations are met.

CWI has initiated the next phase of the development work, with an objective of continuing Beta engine build into 2016 and adding Beta engines to the existing Alpha customer field demonstrations. This leads to commercial availability of the ISB6.7 G engine in a broad range of Class 5 to 7 vehicles, including medium duty trucks, school buses, shuttle buses, yard tractors, and municipal works vehicles such as street sweepers, in 2016. CWI anticipates that the total expense to enable ISB6.7 G commercial availability will be in the range of \$2 million to \$4 million.

## GLOSSARY

Term	Definition
CAD	Computer Assisted Design
CCV	Closed Crankcase Ventilation
CH <sub>4</sub>	Methane
CISPR	English: Special international committee on radio interference
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO <sub>2</sub>	Carbon Dioxide
CWI	Cummins Westport Inc.
DF	Deterioration Factor
ECM	Electronic Control Module
EGR	Exhaust Gas Recirculation
EMD	Engine Manufacture Diagnostics
FIRG	Failure Incident Review Group
FTP	Federal Test Procedure
GHG	Greenhouse Gas
GVW	Gross Vehicle Weight
ICM	Ignition control module
LNG	Liquefied Natural Gas
NO <sub>x</sub>	Nitrogen Oxides
NMHC	Nonmethane Hydrocarbons
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
PM	Particulate Matter
RMCSET	Ramped Mode Cycle Supplemental Emissions
RMEP	Rocky Mount Engine Plant

SESI	Stoichiometric, EGR, Spark Ignition
SLT	System Level Test
ULSD	Ultra Low Sulfur Diesel
U.S. EPA	United States Environmental Protection Agency

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# APPENDIX

Appendix A: Development of an Advanced 6.7 Liter Natural Gas Engine

**This appendix is available as a separate volume, publication number CEC-500-2016-004-AP.**